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A Demonstration of Beneficial Uses of Warm Water from Condensers of Electric Generating Plants

Northern States Power Co.
Minneapolis, MN

Prepared for

Industrial Environmental Research Lab.
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16. ABSTRACT The report gives results of a project to demonstrate that warmed cooling water from condensers of electric generating plants can effectively and economically heat greenhouses. The 0.2-hectare demonstration greenhouse, at Northern States Power Co.'s Sherburne County (Sherco) Generating Plant, used 29.4 C water to heat both air and soil: finned-tube commercial heat exchangers were used to heat the air; and buried plastic pipes, the soil. Warm water from the Sherco 1 cooling tower was piped over 0.8 km to the greenhouse where it was cooled from 2.7 to 5.6 C before returning to the cooling tower basin. Roses and tomatoes were the principal crops in the 3-year test, although other flowers and vegetables, and conifer seedlings were also grown. The warm water heating system supplied all the greenhouse heating requirements, even at ambient temperatures as low as -40 C. Roses, snapdragons, geraniums, tomatoes, lettuce, and evergreen seedlings were grown successfully. The demonstration proved the concept to be both technically and economically feasible at Sherco, with an apparent saving of $4500/hectare in 1978 dollars over fuel oil heating, plus an annual oil savings of about 500 cu m/hectare. Privately financed commercial greenhouses heated with warm water were built at Sherco in 1977. The commercial greenhouses will expand from 0.48 to almost 1 hectare by late 1980.

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PREFACE

Northern States Power Company has been involved with the development of beneficial uses of power plant waste heat since 1970. As construction of the two-unit coal-fired Sherburne County (Sherco) station progressed, accompanied by an intensified energy crisis, waste heat utilization appeared to be economically feasible. With its closed-cycle cooling system and adequate condenser outlet temperatures, Sherco was selected as the site for a warm water greenhouse heating demonstration.

The University of Minnesota Agricultural Experiment Station and the United States Environmental Protection Agency joined forces with NSP in developing a program. The resulting Sherco Greenhouse Project is an excellent example of cooperation by an educational institution, a government agency, and private industry in meeting the challenge of a national energy problem.

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LIST OF ABBREVIATIONS AND SYMBOLS

ABBREVIATIONS

British thermal unit	Btu
British thermal units per hour	Btu/hr
British units per hour per square foot	Btu/hr-ft^2
British thermal units per pound	Btu/lb
centimeter	cm
cubic feet per minute	ft^3/min
cubic meters per second	m^3/s
degrees Celsius	°C
degrees Fahrenheit	°F
foot	ft
foot-Candles	ft-C
gallon	gal
gallons per min	gal/min
gallons per min	gpm
gallons per square foot	gal/ft^2
gigajoule (one billion joules)	GJ
gram	gm
hectare	ha
horsepower	hp
hours	hrs
inch	in
kilogram	kg
kilogram per cubic meter	kg/m^3
kilojoule per kilogram	KJ/kg
kilowatt	kw
kilowatt-hour	kwh
liters per second	l/s
liters per square meter	l/m^2
megawatt	MW
megawatt-hours	MWH
meter	m
million British thermal units	MBtu
ounce	oz
ounces per cubic feet	oz/ft^3
parts per million	ppm
pound	lb
quart	qt
square foot	ft^2
square meter	m^2

SYMBOLS

calcium	Ca
calcium carbonate	$CaCO_3$
carbon dioxide	CO_2
magnesium	Mg
temperature differential	ΔT

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INTRODUCTION

In July 1978, the total electric generating capability of United States power plants was 540,000 megawatts (MW).[1] Assuming that there will be a 3-4% compound annual growth rate, a modest forecast by most utility standards, energy availability by the late 1990's must be doubled. This means that before the year 2000, the nation's power demands will be more than one million MW.

Rapidly increasing demand for electric power requires that each day for the next 20 years, an average of 74 MW of electric power generation will be placed in service in this nation. A high proportion, 80%, of the added generating facilities will be thermal plants, with large volumes of warm water discharged from the condensers.

Using present technology, generating plants are only 35-40% efficient. Putting it another way, nearly two-thirds of the energy required for plant operation is not converted to electricity. Most of the unused thermal energy is rejected by the cooling system and is called waste heat, although the rejected heat is a consequence of the second law of thermodynamics and is not willful waste.

All steam-electric generating stations require huge quantities of cooling water to dissipate waste heat. To protect the environment, most future power plants will be required to install a closed-cycle system of cooling, utilizing cooling towers or cooling ponds. Temperatures of circulating cooling water leaving the condenser in a closed-cycle design are likely to be in the 24°-49°C (75°-120°F) range, considerably higher than the condenser discharge of "once-through" cooling plants. A closed-cycle 1000 MW plant requires cooling water circulated at the rate of 25,240 l/s (400,000 gpm), rejecting nearly 52.8 X 10^6 GJ (50 X 10^{12} MBtu) of waste heat each year.

A truly energy conscious society must recognize the tremendous waste of energy this represents on a national scale. New ways to recapture waste heat should be explored to make the best possible use of non-renewable resources: coal, oil, natural gas, and uranium.

[1]National Electric Reliability Council - July, 1978, Review

CONCLUSIONS AND RECOMMENDATIONS

The Sherco Greenhouse project has satisfactorily demonstrated that power plant condenser discharge water, with a minimum temperature of 29.4°C (85°F), can be used to supply the total heating requirements of greenhouses in a northern climate. The demonstration has proven the technological and economic feasibility of this application of power plant waste heat.

At the same time, it is acknowledged that: (1) the capital investment in a warm water heating system is slightly higher than the investment in a conventional heating system and (2) electric power costs will be greater with a warm water heating system than with a conventional heating system.

If the results of this project are to be successfully applied at other power plant sites, it is recommended that:

(1) Reliability of warm water service be considered by selecting power plants with two or more generating units.

(2) The individual greenhouse owners provide an adequate backup heating system in the event of a warm water supply outage.

(3) The area at the power plant reserved for greenhouses be as close as practicable to the source of warm water.

(4) The greenhouse structure should emp'oy energy saving features such as a double-layer roof and sidewalls.

Northern States Power Company is presently leasing land to private greenhouse operators for the purpose of building waste heat greenhouses. It is intended that the greenhouse owners build and manage their own structures and equipment. The Company will provide a supply of warm water at a fair and reasonable rate reflecting: (1) the capital investment required to deliver the warm water, (2) the operating and maintenance expense connected with the pipeline, and (3) the electric energy necessary to pump the warm water from the power plant to the greenhouse complex.

DESCRIPTION OF FACILITIES

STRUCTURAL FACILITIES

The Sherco Greenhouse is a conventional arch frame, gutter-connected style. The 14 modules, or bays, are each 5.2 m (17 ft) wide by 29.3 m (96 ft) long and represent a covered surface area of 0.21 ha (0.53 acre). The gutter clearance height is 2.4 m (8 ft) with the longitudinal axes of the bays oriented north-south. This type of greenhouse was chosen for the demonstration project primarily because of the lower initial capital cost and because of the wide acceptance of the structural type among greenhouse operators and growers.

The roof covering of the greenhouse is a double layer, air-inflated ultraviolet-resistant polyethylene. The double layer of polyethylene was determined to be the most viable roof covering because of lower initial capital cost, high popularity with growers and primarily because of the higher resistance to heat transfer. Replacement of the roof covering was performed on an annual basis mainly due to the nature of the project with regard to potential failure during the winter heating season. The only problems experienced with the polyethylene roof covering were slight and were associated with damage due to ice formation coupled with high winds during winter sleet storms.

The east and west side walls and south end wall are covered with an outside layer of reinforced corrugated fiberglass panels and an inside layer of polyethylene. The north end wall is covered with an outside and inside layer of polyethylene. The lower portion of the polyethylene on the north wall is raised to act as an outside air intake for the evaporative pad cooling system as shown in Figure 1.

The greenhouse crops and mechanical equipment were arranged to provide north-south bench and row orientation. East-west main walkway access was provided on the south end of the greenhouse and on the north end under the structures used to support the heat exchanger units.

A crop support system was added as a retrofit design, independent of the basic greenhouse structure. The rose support system consists of three layers of galvanized welded wire fabric which extends the full 25.9 m (85 ft) length of each bench. The crop support system for the tomato plants utilizes a wood member frame for supporting overhead horizontal steel pipes. The tomato plants were supported with nylon twine.

The headhouse adjoining the greenhouse is a 12.2 m (40 ft) by 18.3 m

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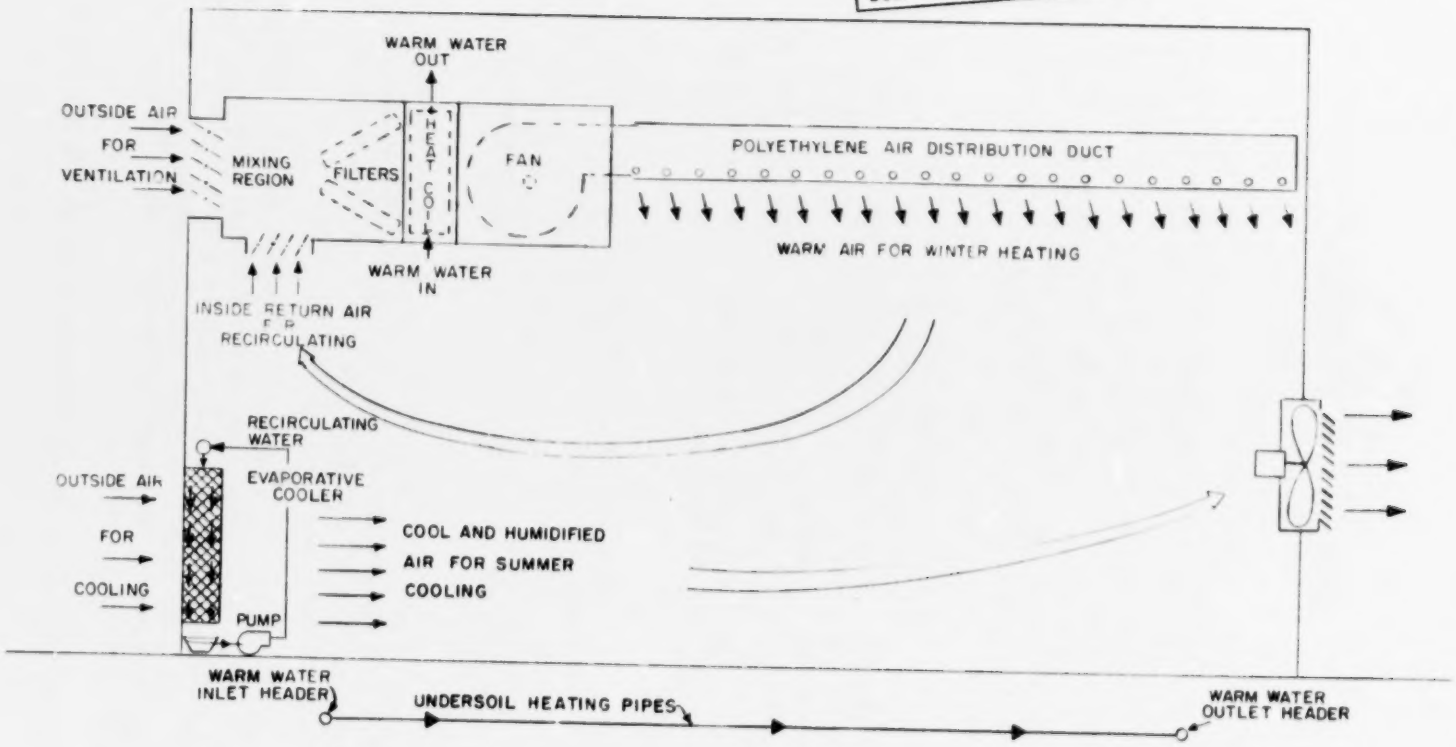


Figure 1 Heating and Cooling System Schematic

(60 ft) steel frame building. The headhouse accommodates space for a production work area, a boiler room, a data acquisition and control room, an office and restroom, a data acquisition and control room, an office and restroom area, a walk-in cooler and a mechanically vented chemical storage cabinet. The headhouse acts as a central facility for all horticultural and mechanical system operations.

AIR HEATING SYSTEM

The heating system employed in the Sherco greenhouse consists of an air heating system and a soil heating system. Warm water is circulated through an underground piping grid to provide crop root zone temperature control and also through finned-tube, forced air heat exchangers.

The air heating system was designed to provide all of the make-up heat requirement of 586 KW (2.0 X 10^6 Btu/hr) at the design conditions of -34.4°C (-30°F) ambient and 10°C (50°F) greenhouse air dry bulb temperature. The water to air heat exchange is accomplished by use of commercially packaged fan/finned-tube heat exchanger units.

Twelve of the 14 greenhouse bays are equipped with 2.24 KW (3 hp) centrifugal air handlers in combination with draw-through finned coils as shown in Figures 1 and 2. The rated heat transfer capability of the coils is 44.5 KW (1.52 X 10^5 Btu/hr) with 29.4°C (85°F) entering water and 10°C (50°F) entering air conditions. At the design water flow rate of 1.87 l/s (29.6 gal/min) and the design air flow rate of 3304 l/s (7000 ft^3/min), the coil outlet conditions of 21.2°C (70°F) air and 23.9°C) (75°F) water temperatures are experienced. Heated air is uniformly distributed by overhead 0.76 m (30 in) diameter perforated polyethylene ducts which extend the full length of the bay.

The two center bays of the greenhouse are equipped with a horizontal discharge (non-ducted) unit heater in each end, oriented to discharge air toward the opposite end heater. These unit heaters, as shown in Figure 3, have circumferential finned-tube coils with 746 W (1 hp) propeller fans. At the design air flow rate of 3260 l/s (6900 ft^3/min) and water flow rate of 1.0 l/s (16 gal/min), these units will effect a heat transfer rate of 17.6 KW (6.0 X 10^5 Btu/hr) from 29.4°C (85°F) entering water to 10°C (50°F) entering air. The unit heaters were installed to permit comparative indications of the economic or technical performance benefits inherent in either type of heat exchanger unit.

BACKUP HEATING SYSTEMS

The greenhouse is equipped with an alarm system which monitors three parameters critical to the environment control system operation. Project personnel are notified of alarm conditions caused by greenhouse air temperatures below 10°C (50°F) (in the event of mechanical equipment failure), by supply water temperatures below 23.9°C (75°F) (in the event of an unscheduled power plant outage) or by an electric power interruption.

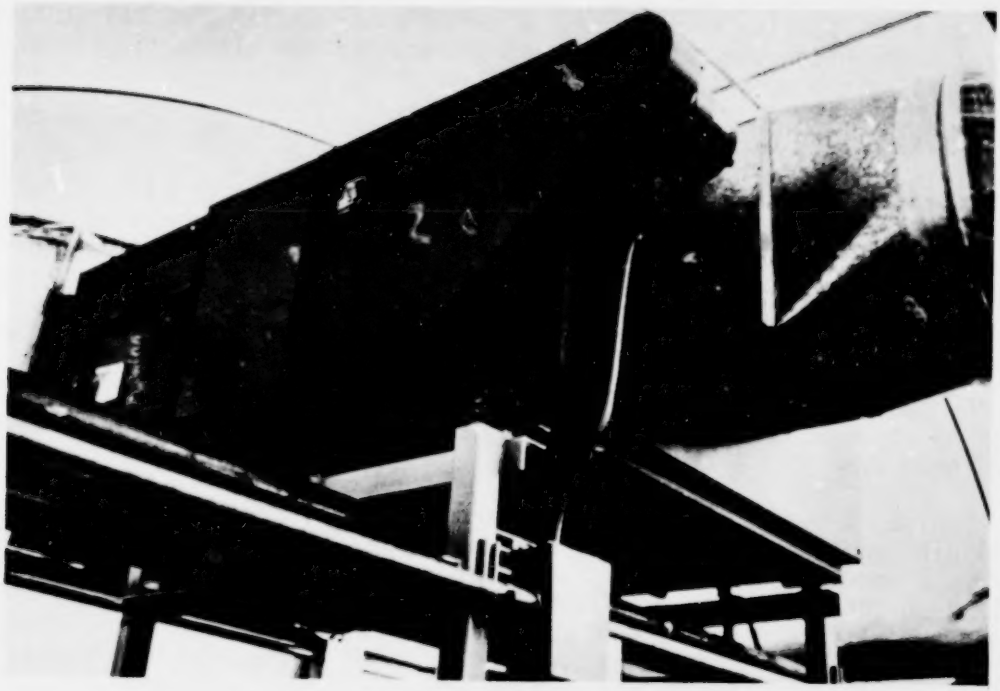


Figure 2 Trane Air Handler

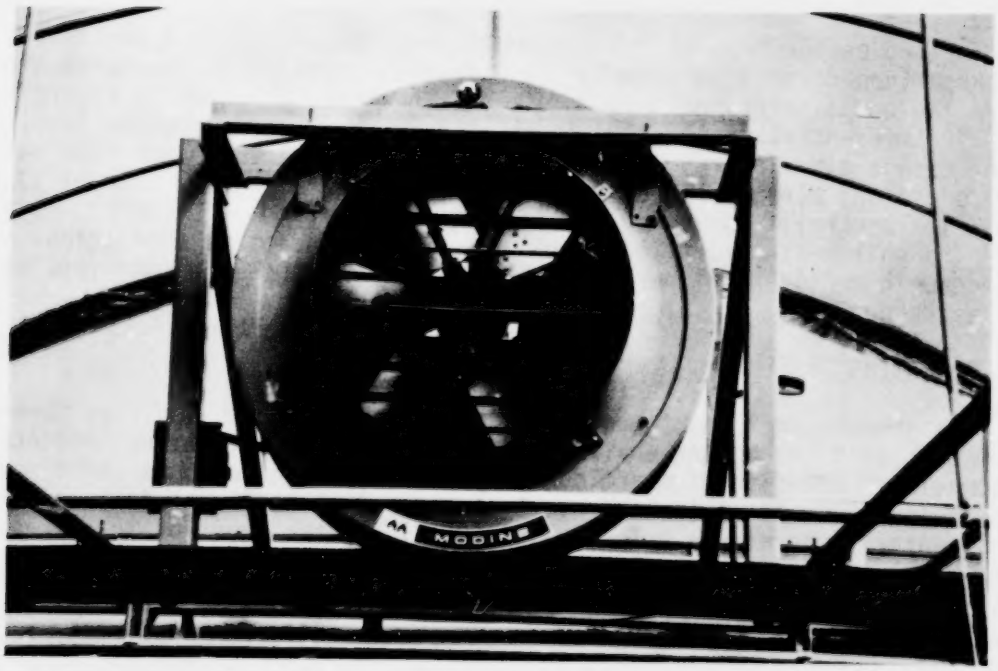


Figure 3 Modine Unit Heaters

Since the greenhouse electric power is not supplied directly by the Sherco plant, two 390 KW (1.28×10^6 Btu/hr) electric hot water boilers serve as a standby heat source in the event of simultaneous, two-unit plant outage. These boilers were used during the 1975-76 heating season to provide heating by simulating circulating water temperatures, before the first generating unit was operating commercially.

In the event of an electric power interruption during the heating season, an emergency heating system is utilized. A 10 KW propane-fueled electric generator provides emergency power for lights and for portable propane heater operation. Six 103 KW (3.5×10^5 Btu/hr), propane-fired, forced-air heaters are deployed in the greenhouse to provide heat until normal electric service conditions are restored. In both electric power interruptions experienced during the past three heating seasons, scant use of the emergency system was necessary because of prompt restoration of normal electric power service.

SOIL HEATING SYSTEM

The soil heating system was installed primarily to provide crop root zone temperature control capability to enhance plant response. While soil heating does provide a small portion of the makeup heat requirements, the air heating system is designed for the total heating required because of the inherent slow thermal response time of the soil heating system.

The installed soil heating system (Figure 4) consists of 2.54 cm (1 in) diameter polyethylene pipes spaced 0.61 m (24 in) on centers and buried approximately 30.5 cm (12 in) below grade. Each bay of the greenhouse contains a grid of 8 pipes and the 14 grids are header-connected to form two systems of seven grids each. The soil heating system is supplied circulation water in parallel with the air heating units (Figure 4) on a demand basis.

The soil heating design water temperature differential is 5.6°C (10°F) with 29.4°C (85°F) supply water at the design flow rate of 0.063 l/s (1 gal/min) per pipe. The temperature differential estimate of 5.6°C (10°F) was based on a 10°C (50°F) soil surface temperature and a 15.6°C (60°F) root zone temperature.

COOLING/VENTILATION SYSTEM

The greenhouse cooling system, as shown schematically in Figure 1, functions independently of the heating system. The conventional evaporative cooling system utilized consists of a 0.91 m (36 in) high cellulose pad mounted vertically to extend the length of the north wall of the greenhouse. Potable water is distributed and recirculated through the pads at a rate of 7.57 l/s (120 gal/min). Air is drawn through the wetted pads by fourteen 0.91 m (36 in) propeller type exhaust fans, with one fan located in the south end of each bay.

The total design cooling air flow rate is 9.2×10^4 l/s (1.95×10^5 ft^3/min) or 6.6×10^3 l/s (13,900 ft^3/min) per bay.

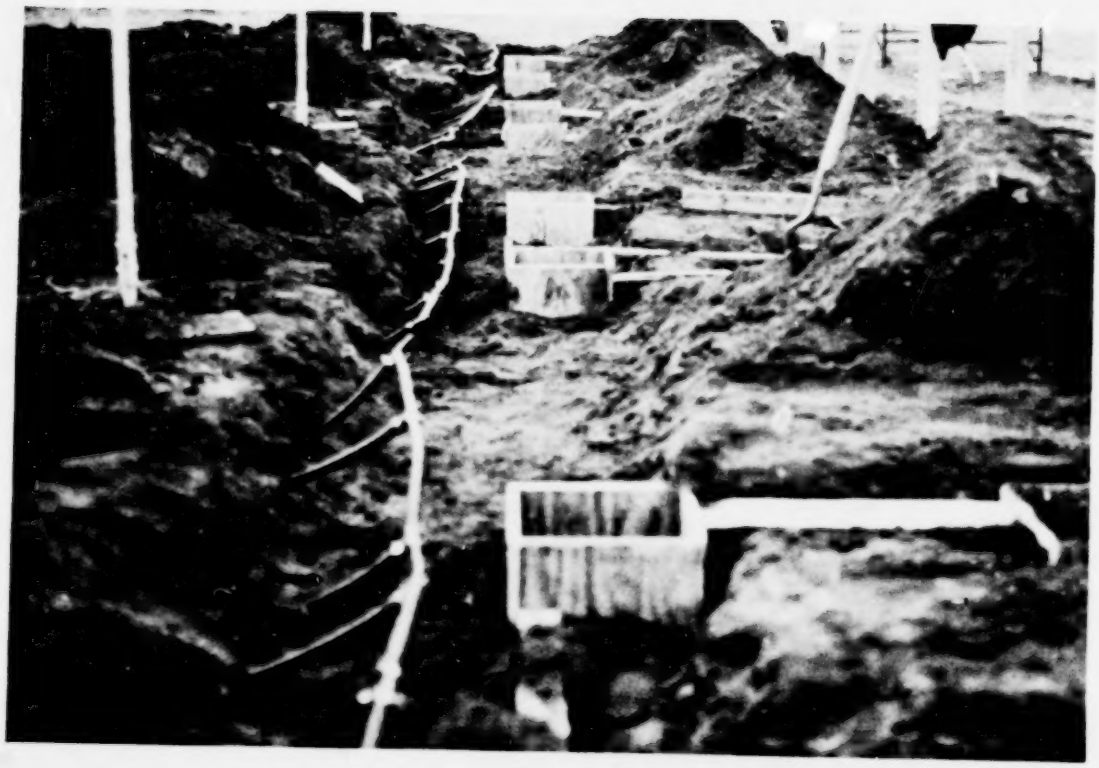


Figure 4 Soil Heating System Headers

All fans and the evaporative pad system are operated automatically with the outside air intake of the pad system fully open during periods when cooling is required. During the moderate temperature transition periods from heating to cooling, ventilation with preheating is provided by operating the centrifugal air handlers with the outside air intake open as shown in Figure 1. During periods with ambient temperature below freezing, the required minimum ventilation is provided by manual operation of exhaust fans drawing outside air through two 0.6 m (24 in) wall louvers located in the two center bays of the greenhouse. As discussed more completely in the control system description, ventilation for humidity control within the greenhouse is provided as a manual function.

GREENHOUSE WATER CIRCULATION SYSTEM

As shown schematically in Figure 5, water circulation through the greenhouse system is provided by primary circulation pumps. From the main supply pipeline, water is pumped through the greenhouse heat exchangers by four 3.73 KW (5 hp) pumps, each of which is capable of circulating 9.47 l/s (150 gal/min). Two pumps operate in parallel per zone on a demand basis, as explained in the control system description. The soil heating system is equipped with one 0.75 KW (1 hp) secondary booster pump per zone, which operates on a demand basis.

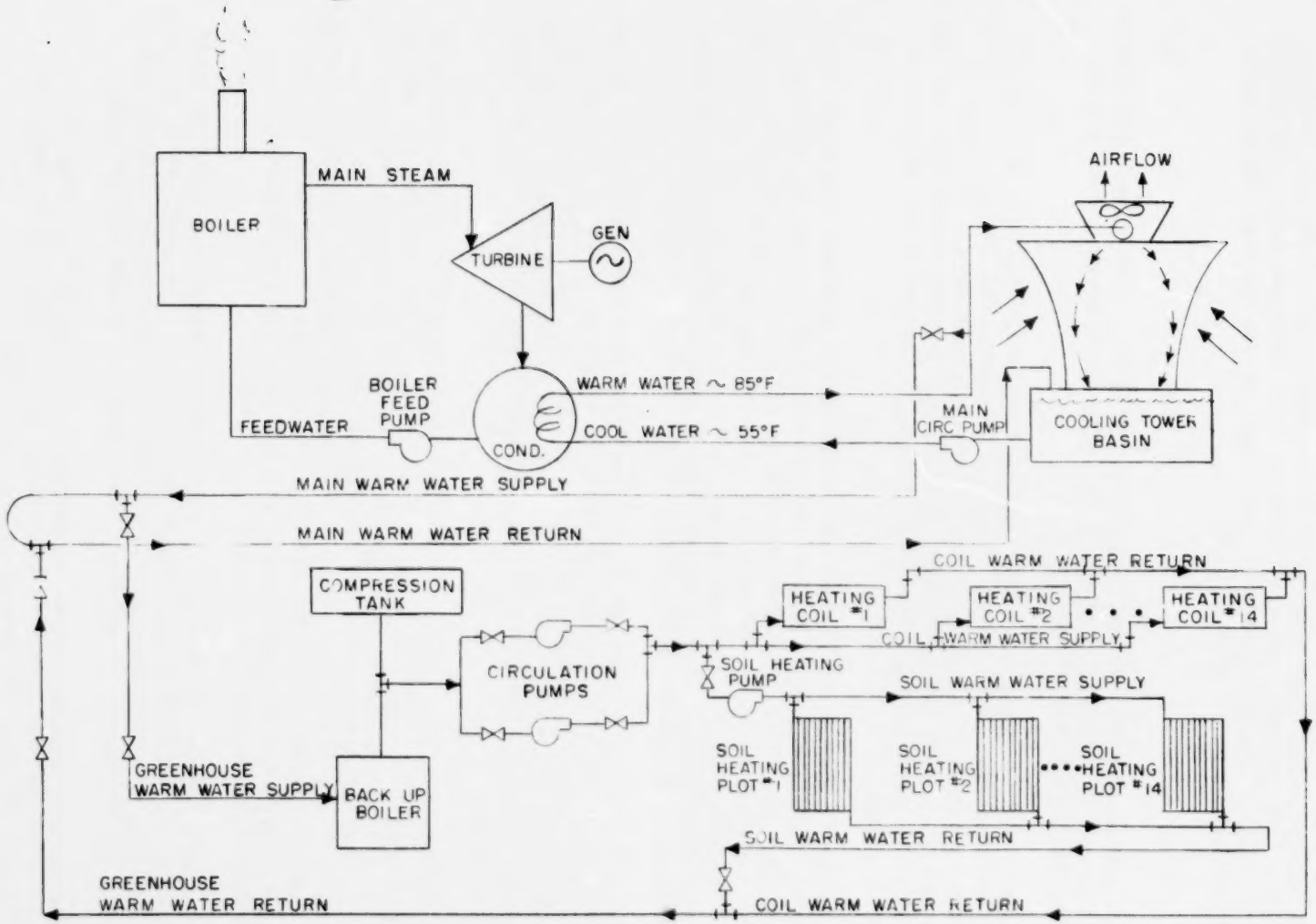


Figure 5 Cooling Water Circulation System Schematic

The design water flow rate of 25.6 l/s (406 gal/min) for air heating and 7.1 l/s (112 gal/min) for soil heating, or a combined total circulation flow rate of 32.7 l/s (518 gal/min), are based on the maximum design water temperature differential of 5.6°C (10°F).

CONTROL SYSTEM

The greenhouse environmental control function is predicated upon simple on-off thermostat control, with dry bulb temperature being the only automatically controlled variable.

Each of the 14 greenhouse bays are equipped with separate heating and cooling thermostats. For control function purposes, the 14 bays are subdivided into two distinct control zones of seven bays each. One zone is further equipped with one additional heating and cooling thermostat per bay and time clock switching to provide differential day and night temperature control setpoints.

A central control and status indication panel provides automatic heating or cooling operation mode selection and selection of outside or return air for heating. Selection of either outside or return air for heating is provided on a manual basis to afford humidity and temperature control in each zone of the greenhouse. This selection is a manually controlled function because of infiltration heat loss and heat exchanger coil freezing problems associated with automatic outside air intake dampers.

The air heating thermostat in any bay initiates the starting of primary pumps for water circulation through the heat exchange coils as well as starting the fan(s) associated with that particular bay. The starting of centrifugal air handlers initiates the delayed opening of return or outside air dampers to prevent rapid inflation damage to the polyethylene air distribution ducts.

A primary starting circuit is incorporated into the control system to provide determinant starting times. That is, the first heating thermostat in a zone starts one of the 3.73 KW (5 hp) primary circulation pumps. The second 3.73 kw (5 hp) pump in the particular zone is started, to operate in parallel with the first pump, when a prescribed number of heating thermostats "made" are activated. When the heating requirements of the zone are satisfied, both pumps are stopped and the initial pump starting sequence is reversed to average overall pump operation time.

The soil heating thermostat in each zone is integrated with the seven air heating thermostats to provide primary control. In addition to primary pump starting, the soil heating thermostats provide starting signals for secondary (0.75 KW/zone (1 hp/zone)) soil heating system booster pumps.

The cooling system control is automatically segregated from heating control. The cooling system is controlled by a thermostat in each bay starting and stopping the appropriate exhaust fans.

DATA COLLECTION SYSTEM

The greenhouse is fully instrumented with an automatic data collection system to provide a complete environmental history and to establish energy balances to assess the technical feasibility of the warm water heating system. A microprocessor-controlled data acquisition and recording system scans 227 data transducers at one-half hour intervals. The data are recorded on paper tape and magnetic tape and are computer processed to provide time function relationships of pertinent environmental and water conditions.

Temperatures are measured at 10 individual points in each of the 14 bays of the greenhouse. Three dry bulb temperatures are monitored at each of three random locations in each bay. The three temperatures measured at each location include one soil temperature, at random depths from 10.2 cm (4 in) to 30.5 cm (12 in) below grade, one air temperature below the plant canopy and one air temperature near the top of the plant canopy. Dew point is also measured at one location in each bay.

The ambient conditions of air, dry bulb temperature and dew point, are monitored at one location outside the greenhouse. Total incident solar radiation is monitored at one location inside the greenhouse and at one location outside the greenhouse at rooftop elevation.

The balance of the points monitored include greenhouse main supply and return water temperatures, soil heating system supply and return water temperatures, and supply and return air and water temperatures on four heat exchangers. Manual readings were also recorded daily of total greenhouse water flow, soil heating water flow and electrical power consumption of circulating water pumps, heating fans and ventilating fans.

Air dry bulb and soil temperatures are measured with 24-gauge, copper-constantan thermocouples, air dew point is measured with heated lithium chloride electrical hygrometers and water temperatures are measured with immersion type copper-constantan thermocouples. Solar radiation is measured by star pyranometers and is recorded as hourly integrated values.

HEATING SYSTEM PERFORMANCE AND OPERATING EXPERIENCE

Operation of the warm water heating system began in December, 1975. Since the Sherco Greenhouse was operational before the start up of Sherco Generating Unit I, condenser waste heat temperatures were simulated by the use of electric boilers. In the 1975-76 heating season, the primary heating objective was to verify the heating system design. Water flow rates, air flow rates, temperature drops, greenhouse heat demand, and other variables were observed and recorded manually for comparison with design values. Several simulation runs using 29.4°C (85°F) water confirmed the design capability of the heating system to transfer the heat necessary to maintain greenhouse air temperatures in an acceptable range of 13-16°C (55-60°F) on the coldest nights, -29°C (-20°F), experienced.

In September, 1976, the Sherco Greenhouse was first supplied heat directly from Sherco Generating Unit I. The heating objective during the winter of 1976-77 was to verify that the waste heat available from the operating power plant was adequate for heating the Sherco Greenhouse. By utilizing an automatic data logger, 227 data points were monitored and recorded at 1/2 hour intervals throughout the heating season, including all heat transfer and greenhouse environmental parameters of interest. This comprehensive data set proved beyond all doubt the technical feasibility of utilizing actual power plant waste heat to provide a suitable greenhouse environment for the production of floral and vegetable crops.

In the third year of operation, the 1977-78 heating season, the main technical objective was to solve some heat exchanger and pipeline fouling problems identified in the previous heating season. Of course, additional heating system performance data were taken and analyzed to add to the body of experience previously gained. Of particular interest in the 1977-78 heating season was the observation of the variation of condenser outlet water temperatures with generator unit loading. Prior to the 1977-78 heating season, the Sherco Generating Plant had only one operating unit. With the addition of Unit II, the station began to operate as a load following rather than baseload facility.

In order to completely document the technical performance of the Sherco Greenhouse Project, particularly the heating system performance, the balance of this section of the report is divided into three parts, each dealing with a specific aspect of the technical performance of the heat source, the heat delivery, and heat transfer systems.

SEVERE COLD WEATHER PERFORMANCE DATA

The greenhouse heat loss reached near design conditions when outside ambient air temperatures fell to -29 to -34°C (-20 to -30°F). Oftentimes when this occurred, the waste heat warm water available from the power plant was significantly warmer than the design temperature of 29.4°C (85°F). For example, Figure 6 shows the condenser outlet water temperature available to the pipeline for delivery to the Sherco Greenhouse on January 9, 1977. This date was chosen because it was the coldest day ever recorded during the project. The corresponding generator unit output shown in Figure 6 is typical of baseload operation of the Sherco Generating Plant. As indicated in Figure 6, a 24-hour average condenser outlet water temperature of 37.6°C (99.6 F) was recorded. At the same time, the average water temperature measured at the greenhouse inlet was 36°C (96.2°F) shown in Figure 7. The average ambient air temperature on January 9, 1977 was -31°C (-23.8°F), with a high of -23°C (-10°F) and a low of -42°C (-42.9°F) at 8:00 a.m. The heat transfer systems in the greenhouse were able to maintain an average greenhouse air temperature of 15°C (59.5°F) with an 8:00 a.m. low of 14°C (58°F) using warm water available at 33°C (91.1°F).

The complete air and soil heating system ΔT averaged 3°C (5.3°F) while the inside to outside air ΔT averaged 46°C (83.3°F). The 24-hour average heat transfer rate based on the total design water flow rate of 32.7 l/s (518 gpm) was 402 KW (1.4×10^6 Btuh).

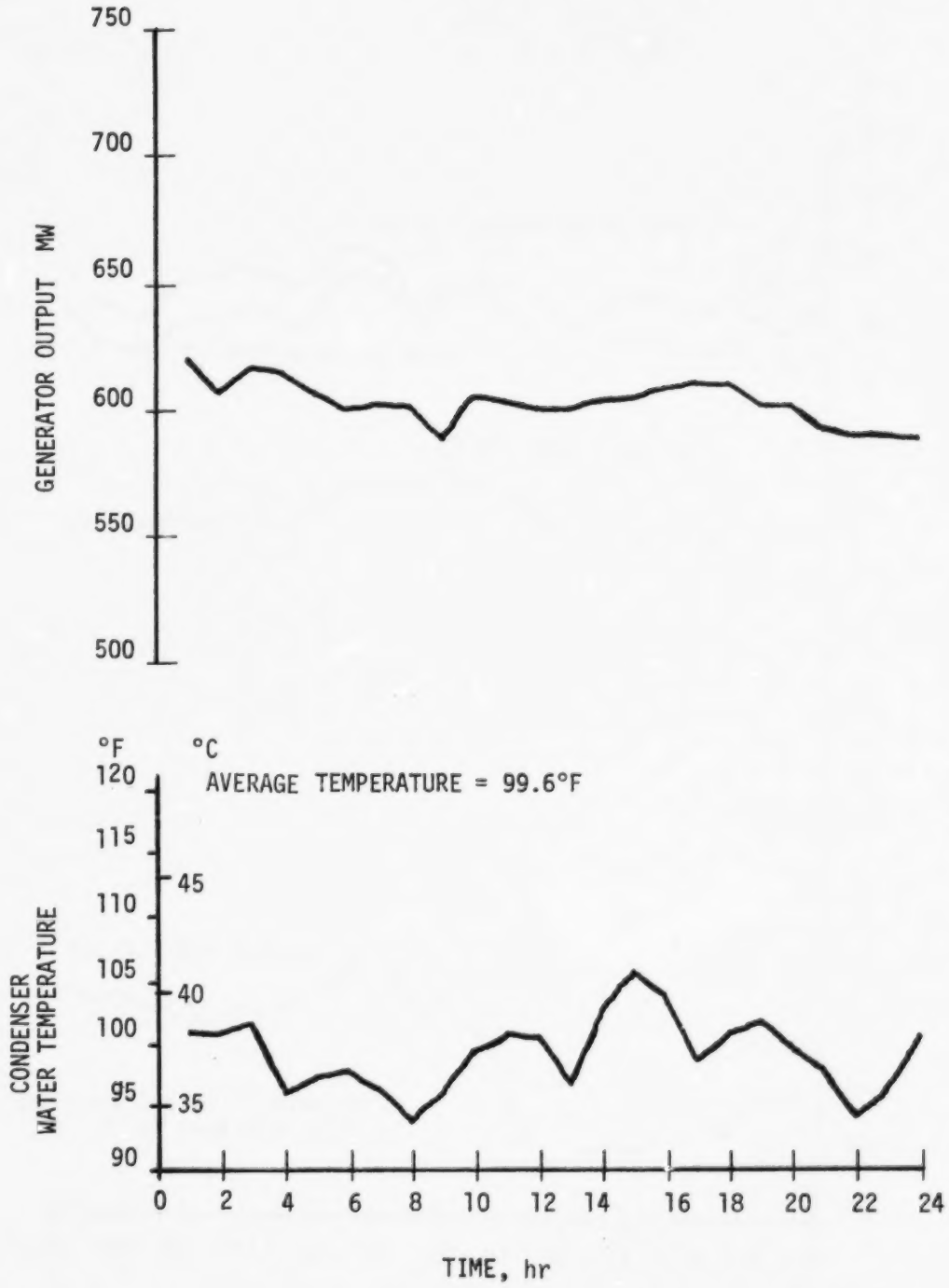


Figure 6 Unit 1 Gross Electrical Output and Condenser Outlet Water Temperature January 9, 1977

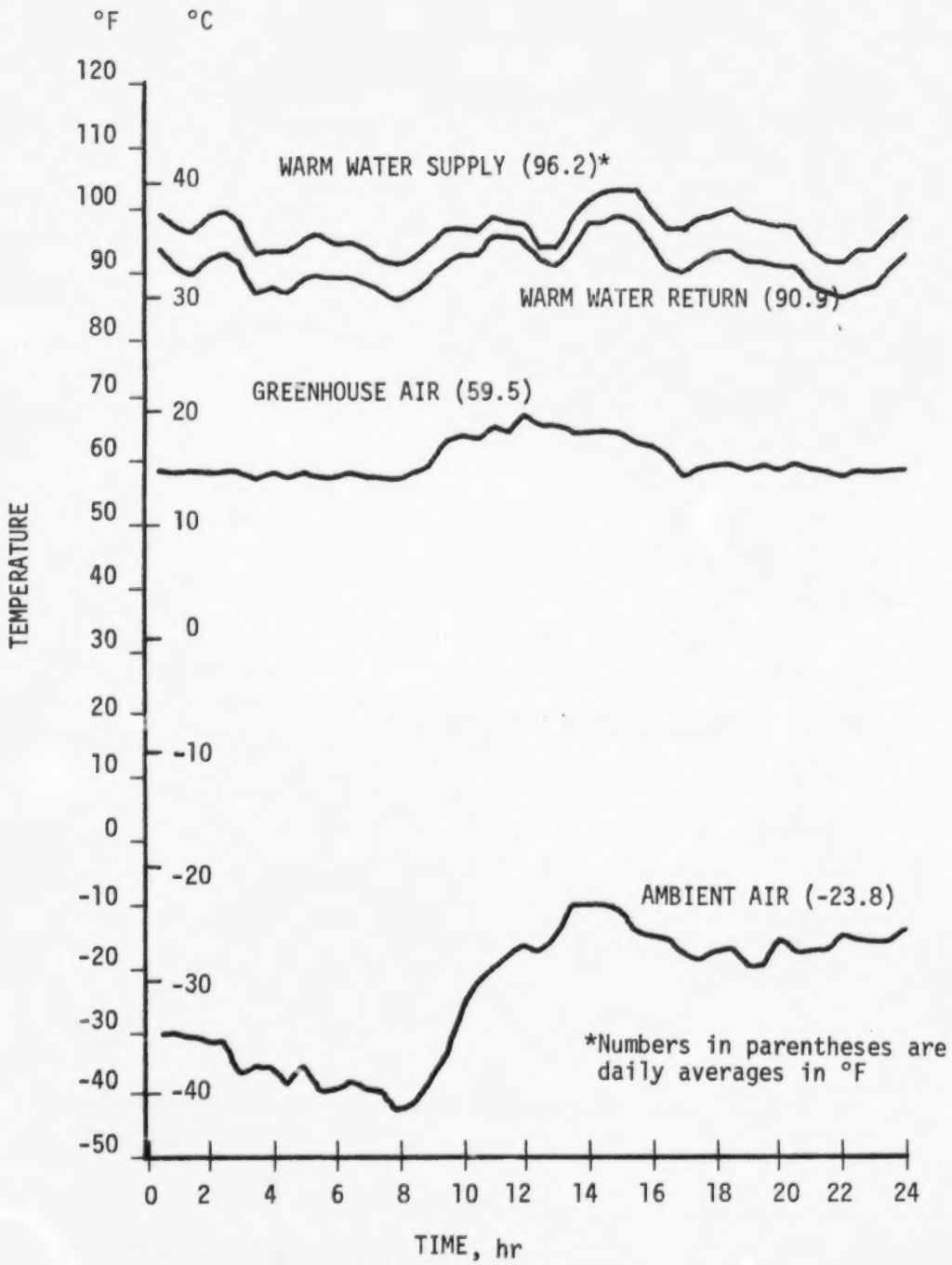


Figure 7 Heating System Performance January 9, 1977

Wind and solar radiation data for January 9, 1977 are presented in Figures 8 and 9 to complete the 24-hour environmental history. The wind velocity data were those recorded by the National Weather Service at St. Cloud, Minnesota about 20 miles northwest of the Sherco Greenhouse. Solar data were measured inside and outside the greenhouse with pyranometers and the hourly integrated values were recorded. From these data, it is obvious that January 9, 1977 was not a completely typical cold day with 40% cloud cover from sunrise to sunset; but, the light winds were fairly typical.

Additional severely cold weather performance data are plotted in Figures 10 and 11. The dates selected represent the two coldest days on record in the 1976-77 and 1977-78 heating seasons. January 10, 1977 was nearly as cold as January 9, and the second coldest day recorded during the project. It differed only slightly from the previous day in that clear skies prevailed from sunrise to sunset. Again, greenhouse air temperatures were held above 14°C (58°F) during darkness hours when ambients dipped to -33°C (-28°F) using waste heat available at 37°C (98.5°F), 24-hour average temperature.

Figure 10 indicates the same data for January 9, 1978, which coincidentally was the coldest day of the 1977-78 heating season. It may be noted that the waste heat was available at slightly higher temperatures, but the greenhouse air temperature was actually lower. No abnormal environmental conditions were noted to explain the apparent difference from previous data. It is possible that reduced temperature set points on the greenhouse thermostats controlled the temperature to the lower than expected value.

Figure 12 is the same data for February 2, 1978. Here, satisfactory space temperatures were maintained in the greenhouse when the waste heat source water temperature was 32°C (90°F), near the design water temperature, and ambient outside air was -20°C (-4°F).

More insight into heating system performance can be gained by a detailed look at the performance of the air heating and soil heating systems separately. Figure 13 shows the finned-tube heat exchanger inlet and outlet water and air temperatures for the 24 hours of January 9, 1977 as measured at the heat exchanger located in the easternmost bay of the greenhouse. The inlet air temperature to the heat exchanger was essentially the average air temperature in that particular bay of the greenhouse. It can be seen that the water was being cooled approximately 4°C (8°F) while air was being heated 9°C (16°F). Both the waterside and airside ΔT's were below design values. The logarithmic mean temperature difference of the heat exchanger averaged 14°C (25.3°F) with an average heat transfer rate of 24.4 KW (117,450 Btu/hr) at the design water flow rate. This measured performance was 60% of the design value as a result of heat exchanger tubeside fouling. However, due to the average warm water temperature being 6°C (11.2°F) above design, the potential adverse consequences on greenhouse air temperature were avoided.

Typical soil heating performance data are shown in Figure 14 for January 9, 1977. The soil temperature plotted is the average of 42 soil temperatures measured at depths varying from a 2.5-30 cm (1-12 in) through the total 2123 m^2 (22,848 ft^2) growing space. The water ΔT in the soil heating system was relatively constant at 3°C (6°F). Since water flow in the system was

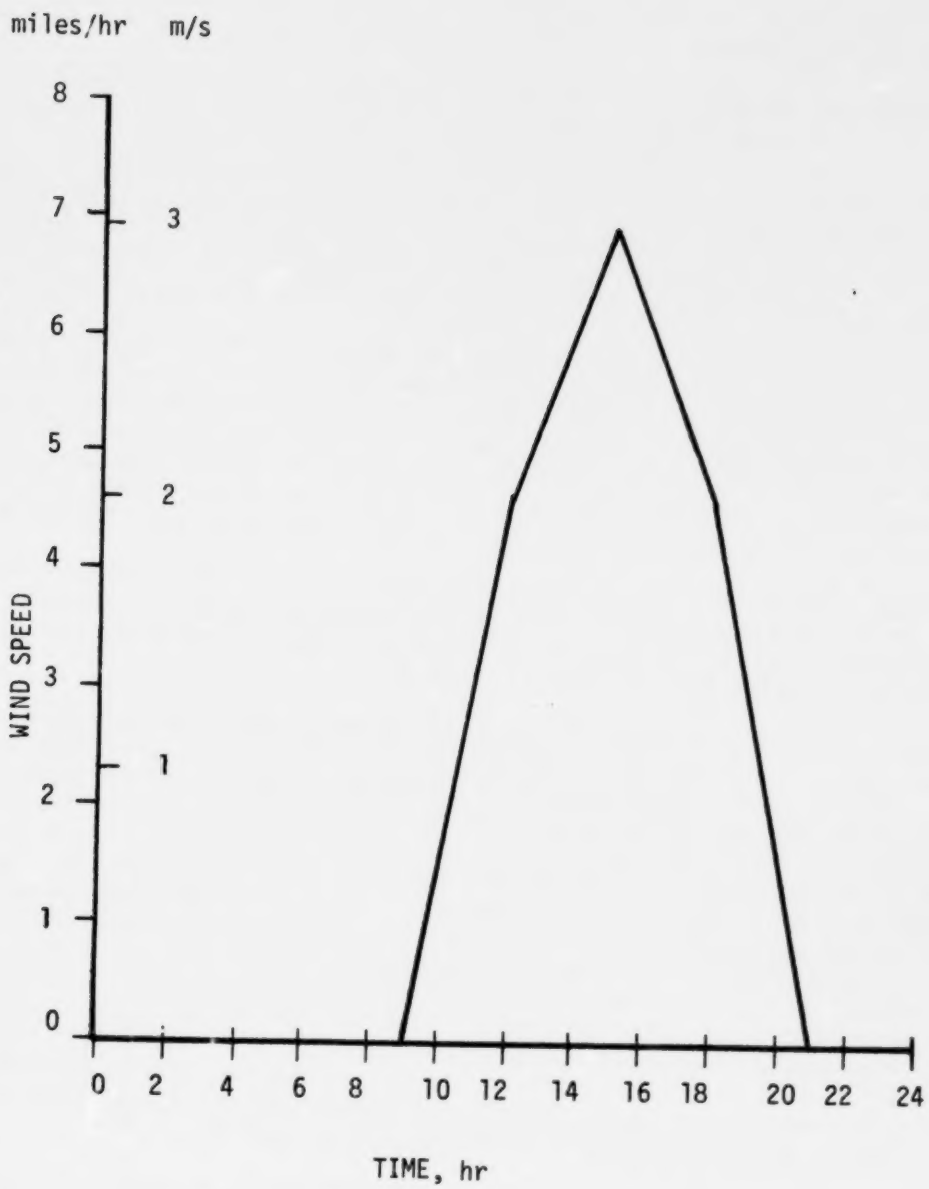


Figure 8 Wind Speed January 9, 1977

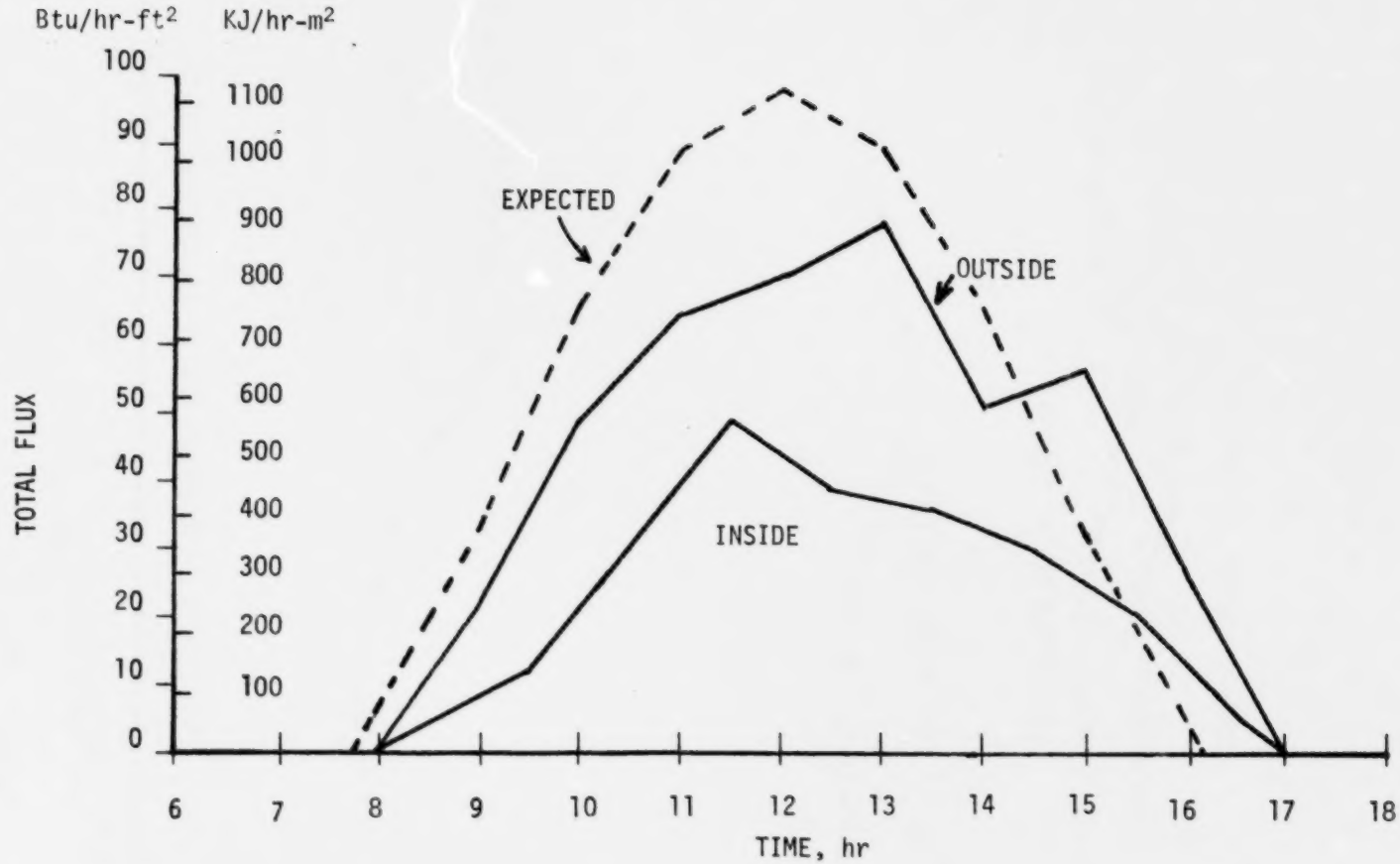


Figure 9 Measured Hourly Average Total Solar Radiation January 9, 1977
Sunrise to Sunset Sky Cover = 40%
Wind Speed = 5.75 miles/hr from East

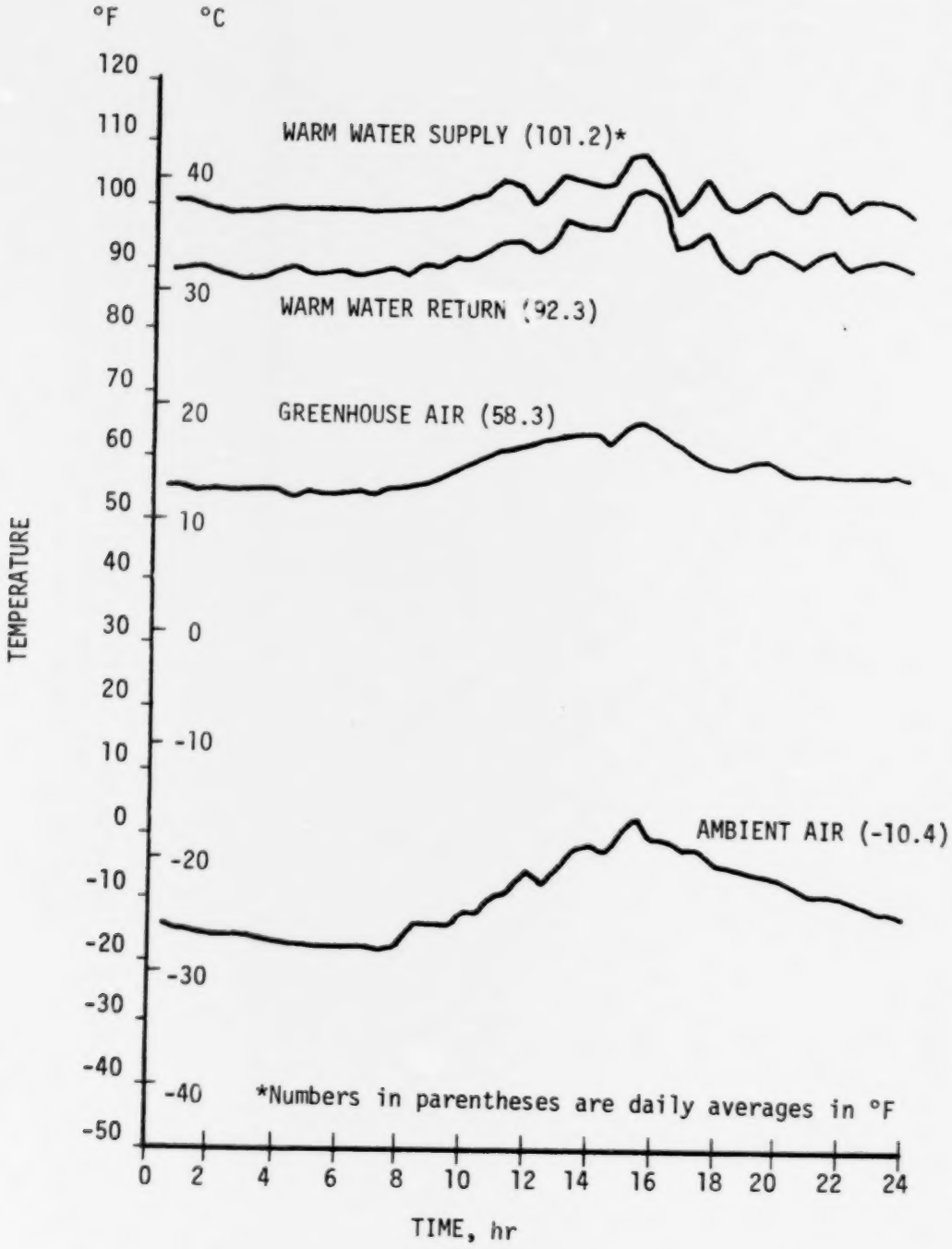


Figure 10 Heating System Performance January 9, 1978

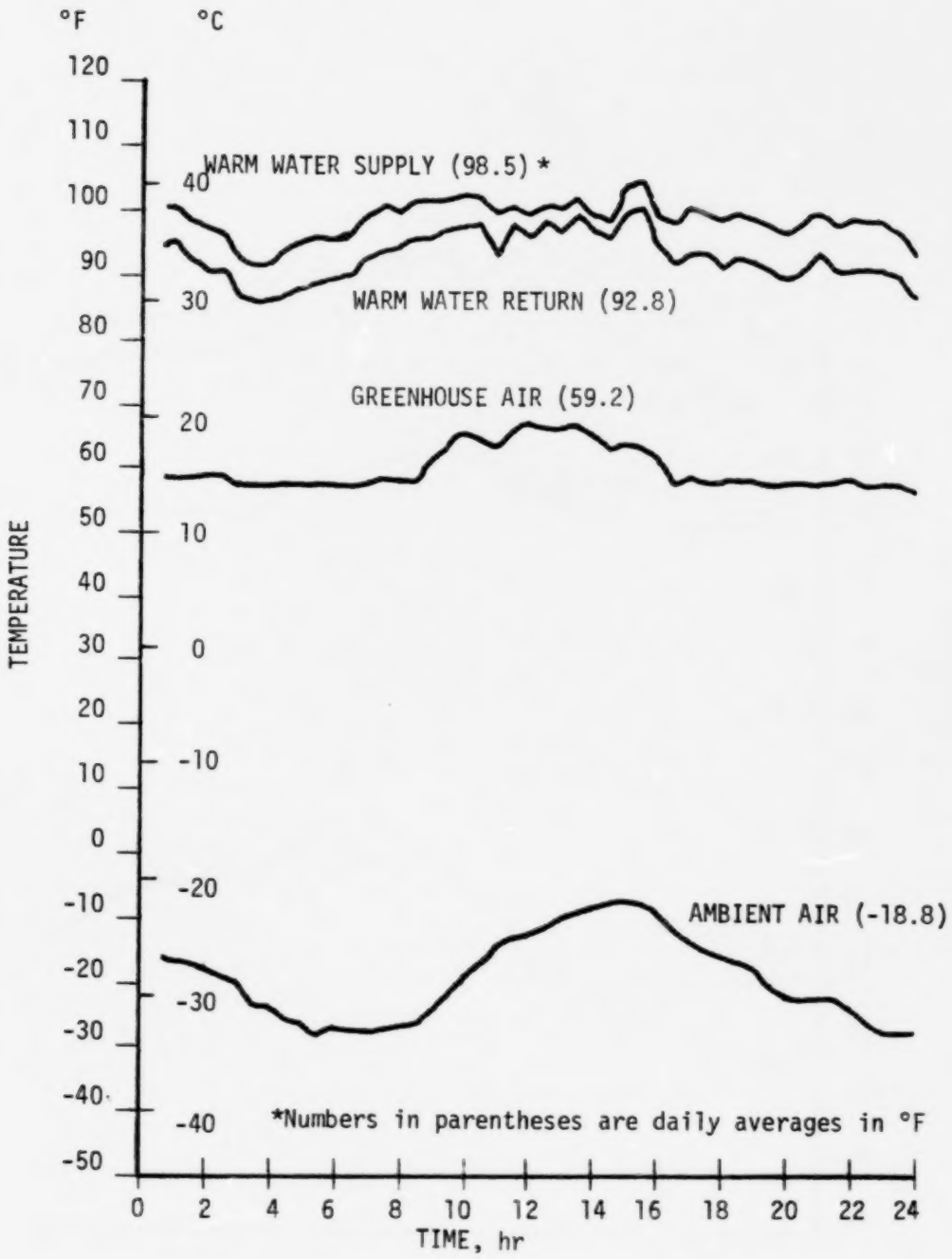


Figure 11 Heating System Performance January 10, 1977

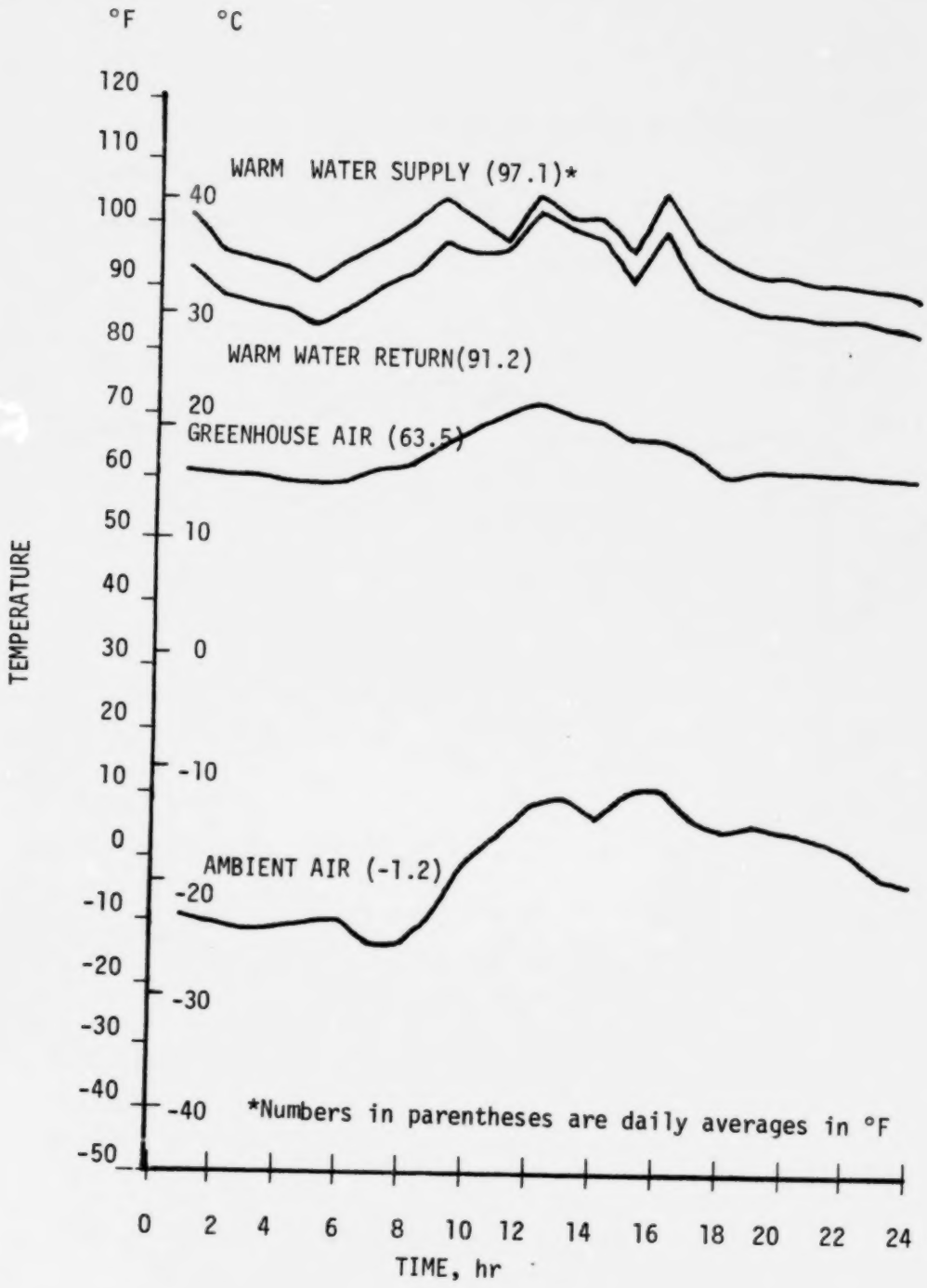


Figure 12 Heating System Performance February 2, 1978

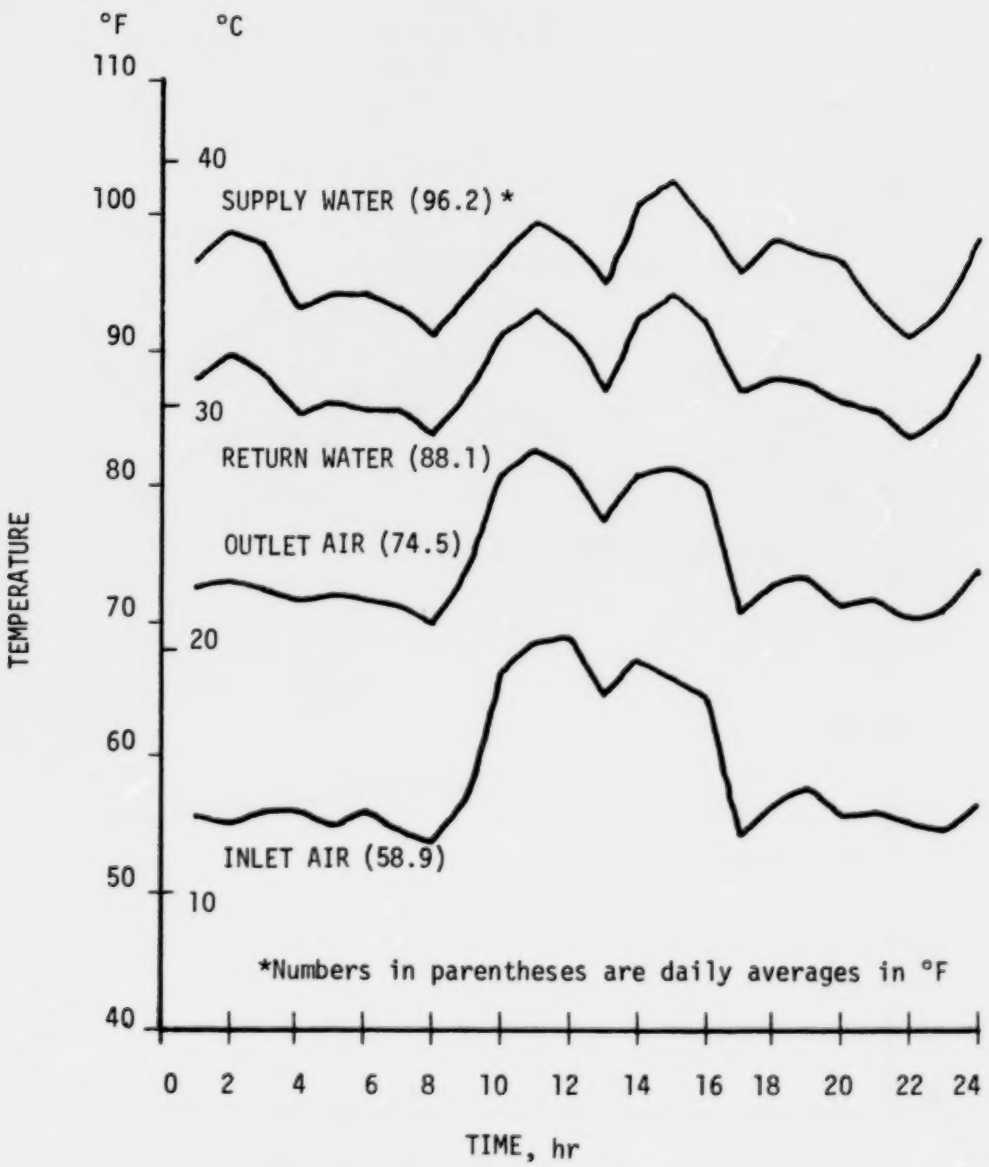


Figure 13 Air heating System Performance January 9, 1977

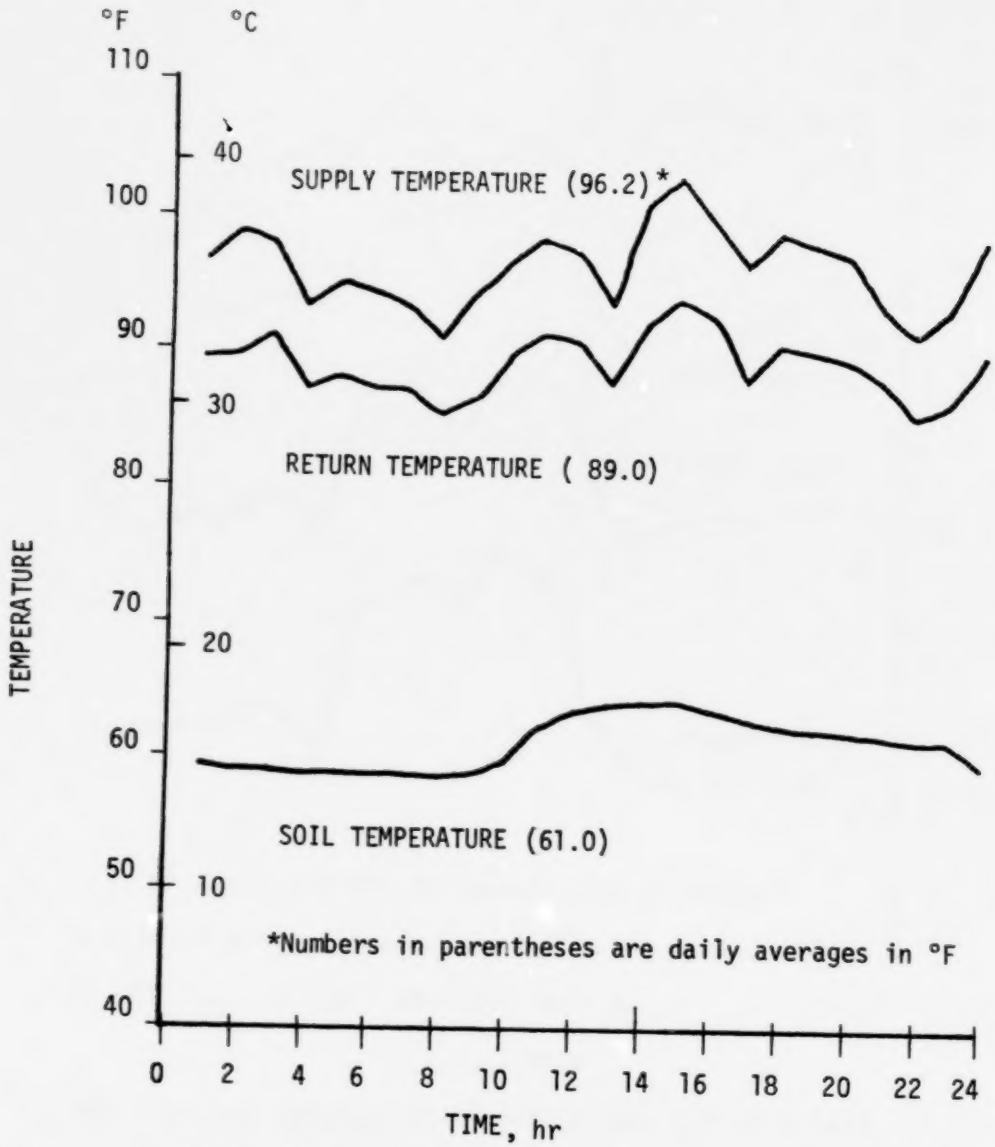


Figure 14 Soil Heating System Performance January 9, 1977
Sunrise to Sunset Sky Cover = 40%

also constant, the design flow rate of 7 l/s (112 gpm) gave a nearly constant heat transfer rate of 98.4 KW (336,000 Btu/hr) or 46 watts/m^2 (14.7 Btu/hr-ft^2). However, the measured water flow in the soil heating system was normally about 5 l/s (80 gpm); thus, a heat transfer rate of 70.3 KW (240,000 Btu/hr) or 33 watts/m^2 (10.5 Btu/hr-ft^2) was actually achieved. This contrasts with the air heating system design heat transfer rate of 295 watts/m^2 (92 X 10^6 Btu/hr-ft^2) of greenhouse floor area. The rise in soil temperature after 10:00 a.m. in Figure 14 is apparently due to higher water temperatures in the heating grid, higher air temperatures in the greenhouse, and higher solar radiation heat flux. Thus, soil heating amounted to a little more than 10% of the total heat transferred, but some of this heat was lost to the earth and did not contribute to heating the greenhouse air.

Besides the coldest day data, the monthly overall performance during January, 1977 and January, 1978 has been analyzed. Figures 15 and 16 present the distribution of warm water and average greenhouse air temperatures for the month of January, 1977. Because Sherco Generating Unit I was operating more or less base loaded, 29.4°C (85°F) water was available 99.6% of the time. With this warm source water, it was straightforward (in spite of heat exchanger fouling) to maintain greenhouse air temperatures above 13°C (55°F) 99.9% of the time.

Figure 17 shows the waste heat temperature distribution available for greenhouse heating January, 1978. These data were taken from plant operating logs and are a composite of the operating data for the two-unit station. In January, 1978 an interconnected pipeline system was in operation so that waste heat could be made available from either generating unit in the event of unit outages. By careful manual selection of the waste heat source, it was possible to provide waste heat at a temperature above 29.4°C (85°F), 73% of the time, even though Unit I and Unit II produced warm water greater than 29.4°C (85°F) only 50% and 65% of the time, respectively. With the available waste heat, air temperatures in the Sherco Greenhouse were maintained above 13°C (55°F) 86% of the time (Figure 18). The difference between January, 1977 and January, 1978 resulted from the change in plant operation from a single-unit baseload station to a two-unit load following station. When operating in an electric system load following mode, the gross electrical output of each unit can vary from 700 MW in the daytime down to a minimum load of about 300 MW in the nighttime. This electrical load variation can result in an 8°C (15°F) change in condenser outlet water temperature as illustrated in Figure 19.

ELECTRIC ENERGY CONSUMPTION

Of particular concern in the design of mechanical systems to utilize waste heat is the operating electrical energy requirement. In order to assess the overall feasibility of waste heat utilization for greenhouse heating, careful records of electrical energy consumption were maintained. Manually read electric meters were installed to measure separately the electric energy consumption of the Sherco Greenhouse air heating system fan motors, water circulation system pump motors, cooling system fan motors, and

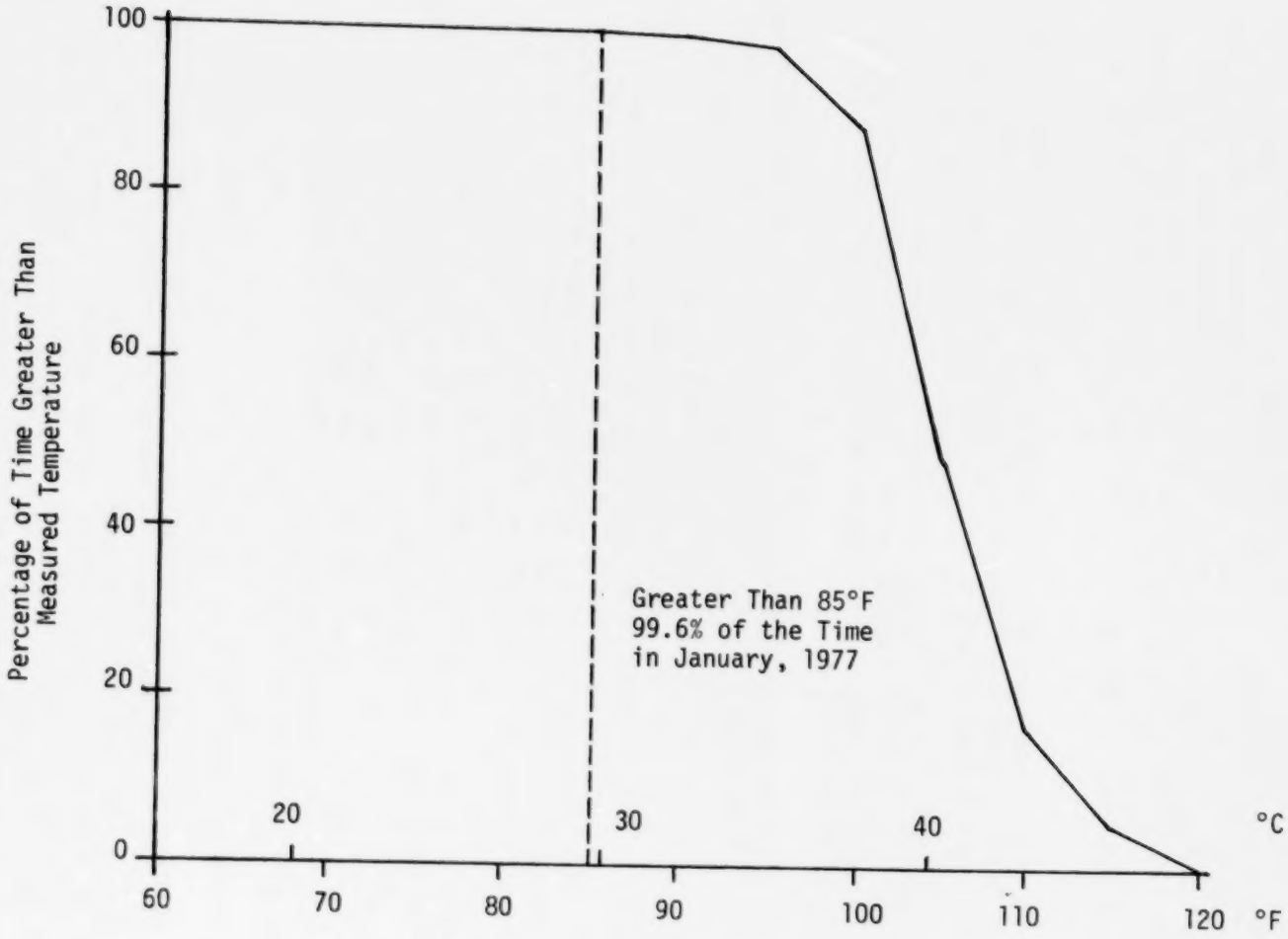


Figure 15 Typical Warm Water Temperatures

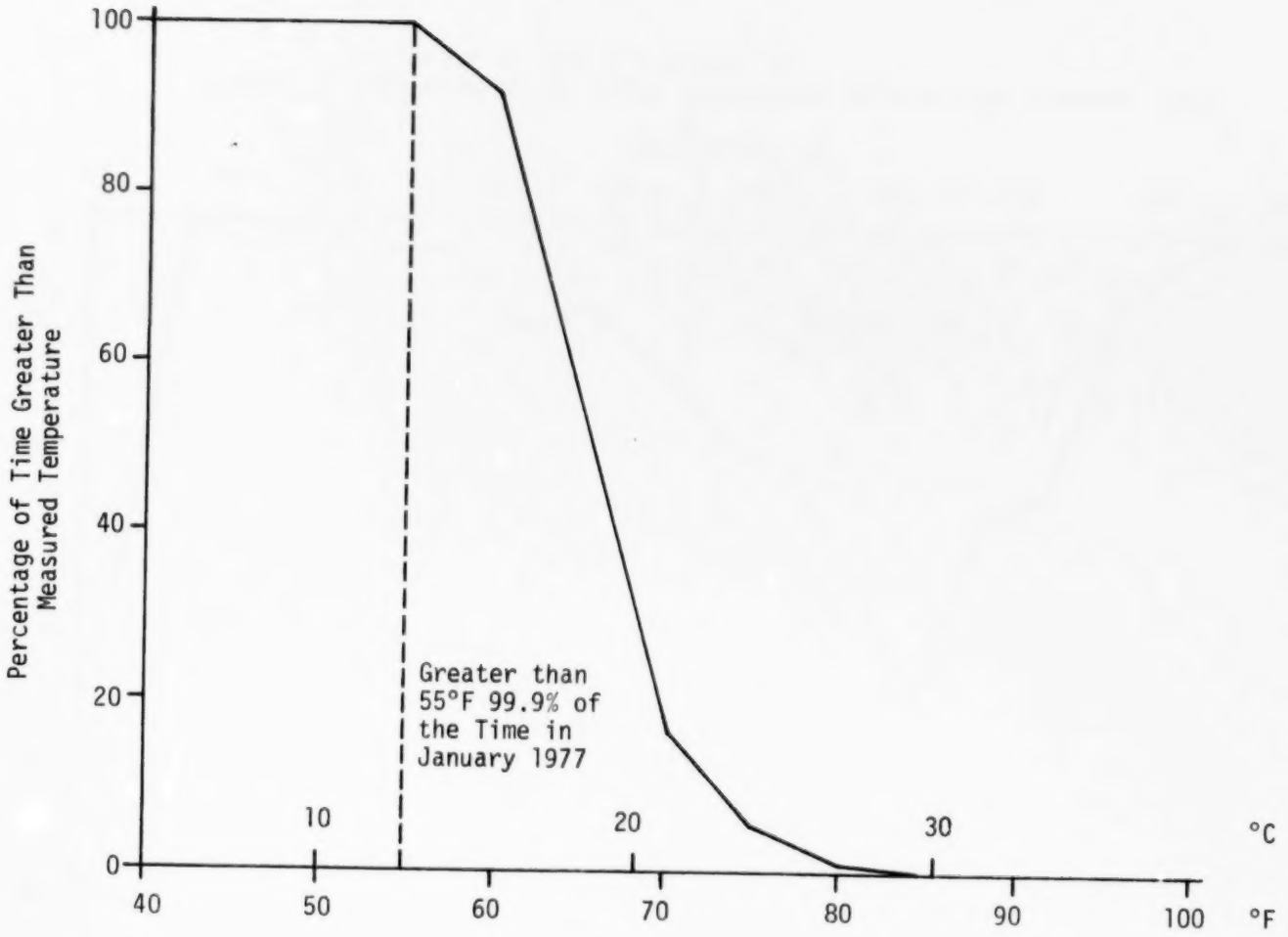


Figure 16 Typical Greenhouse Air Temperature

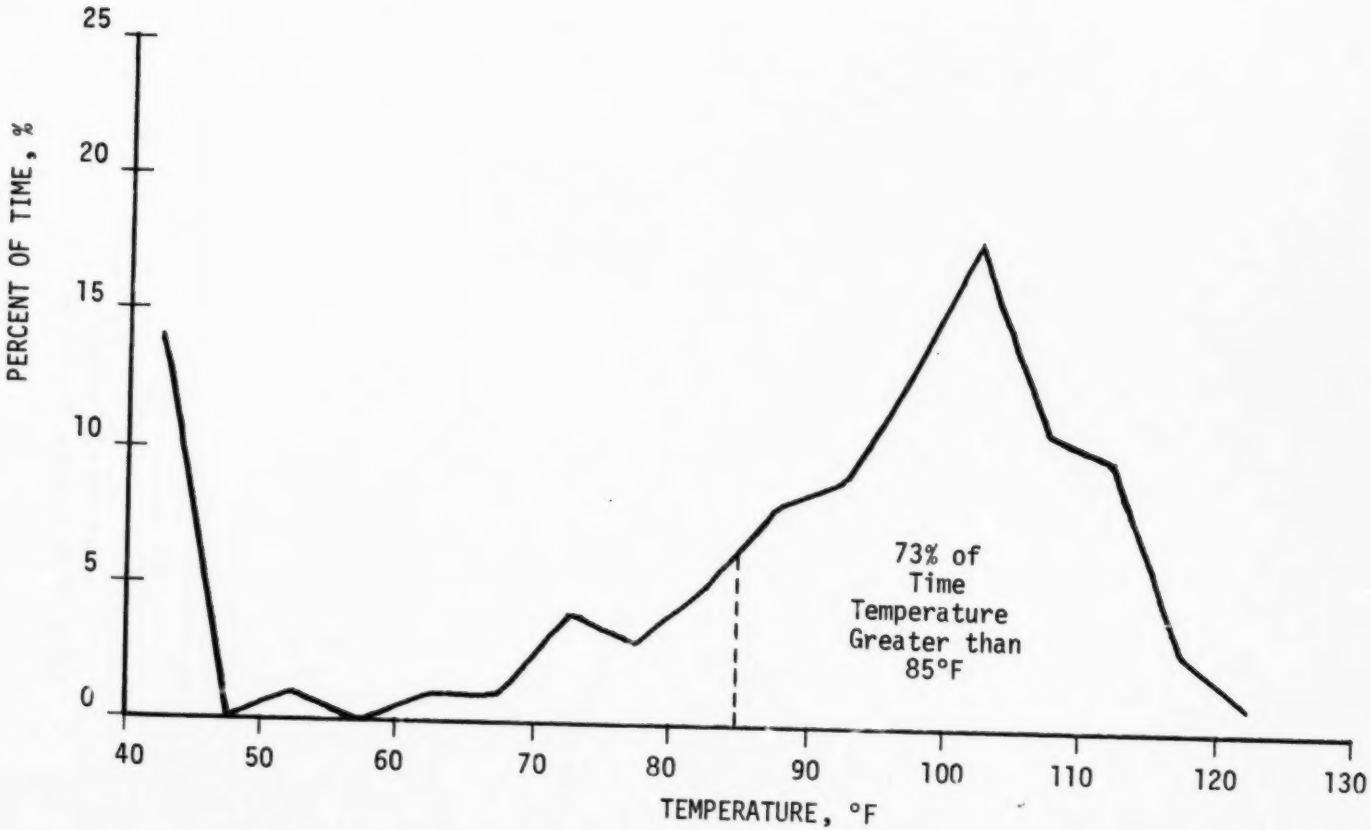


Figure 17 Condenser Outlet Water Temperature Distribution January, 1978
Composite of Unit I and Unit II

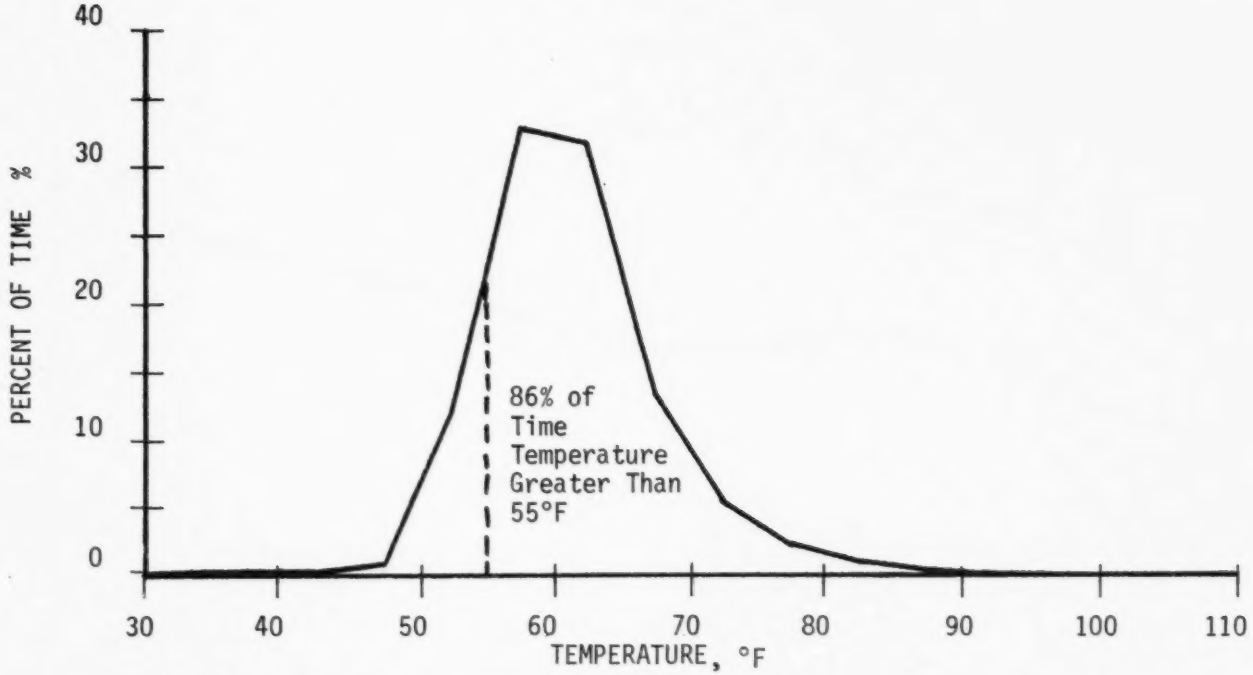


Figure 18 Average Greenhouse Air Temperature Distribution January 1978

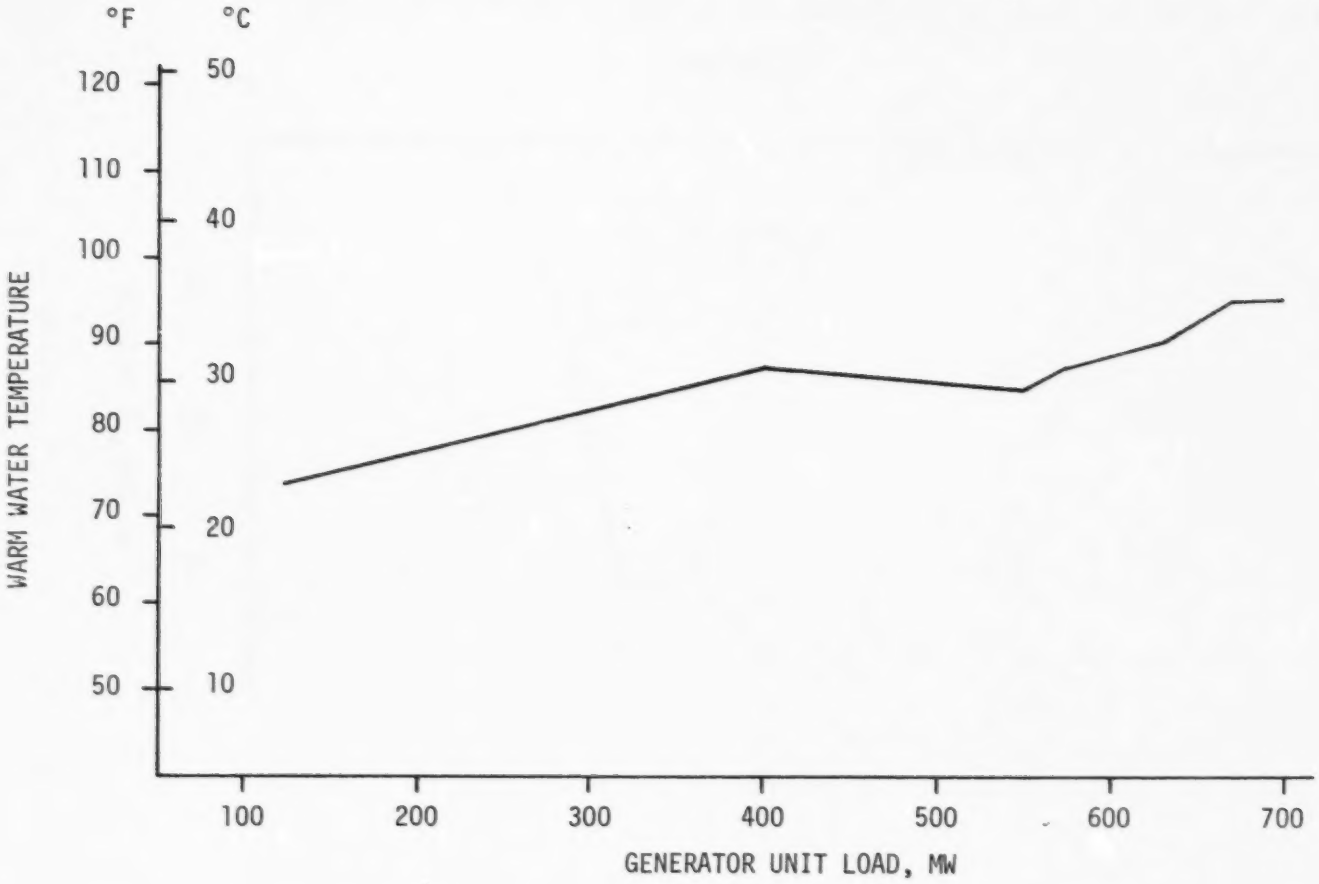


Figure 19 Typical Warm Water Temperature Variation with Unit Load

miscellaneous electrical usage. Back up heating energy supplied by electrical boilers was determined by subtracting all the separate readings from the Sherco Greenhouse master service meter.

Figure 20 shows the monthly total power consumed by the heating fans and circulating water pumps in the greenhouse during the 1976-77 heating season. Beginning in October the curve shape is characteristic of the heating degree days associated with each month of operation. It should be noted that the weather turned abnormally cold in November with 1249 heating degree days compared to a normal of 1050. In contrast, February was abnormally warm with 1283 heating degree days as opposed to a normal of 1448. One may notice that the peak electric energy use of the pump motors is nearly 80% of that of the fan motors even though the installed pumping capacity is one half that of the fans. This is due mainly to two factors: the method of flow control (parallel pumping) and over capacity in the pumping system. The sharp decline in pumping energy consumed in February resulted from using half of the installed pump capacity, in addition to the change in the weather conditions. The sharp rise in March was due to continuous operation of one half of the pump capacity to facilitate heat transfer measurements.

Using the previous data, Figure 21 was generated to show what percent of the installed heating system capacity was used on a monthly average basis. These data proved useful in estimating the electric energy use that commercial operations might expect. Again, it may be noted that the water pumping capacity factors are high, compared to the fans because only four pumps can start or stop; whereas, the air heating system can start or stop 14 fans.

Table 1 summarizes the annual electrical use of all the greenhouse systems. For 1976-77, the period covered is October 1, thru May 31, while in 1977-78 a complete year starting and ending on June 1 is presented. The amount of electrical energy consumed by the warm water heating system fans and pumps was greater in 1977-78 due to the longer period covered and due to the differences in warm water temperatures available from the power plant. The total energy consumed by the fans and pumps in 1977-78 is estimated to be 8.5% of the total energy required to heat the greenhouse during the year. Thus, the warm water heating system had an annual ratio of heat delivered to electric energy consumed of 11.8, which would be equivalent to a heat pump COP of the same value. The instantaneous ideal rated heat output to electric energy input of the Sherco Greenhouse heating system is 12.7.

The energy consumed by the backup heating boilers was necessitated by pipeline outages, reduced condenser outlet water temperatures, and generator unit outages.

A total of 642 hours of operation without waste heat available were recorded from October 1, 1976 to April 25, 1977, at which time the pipeline was shut down for maintenance. Therefore, with an overall availability of warm water waste heat of 75% for the period October through May, backup electrical energy during the first heating season amounted to 249,661 kwh or about 16% of the total calculated annual energy required. Figure 22 shows

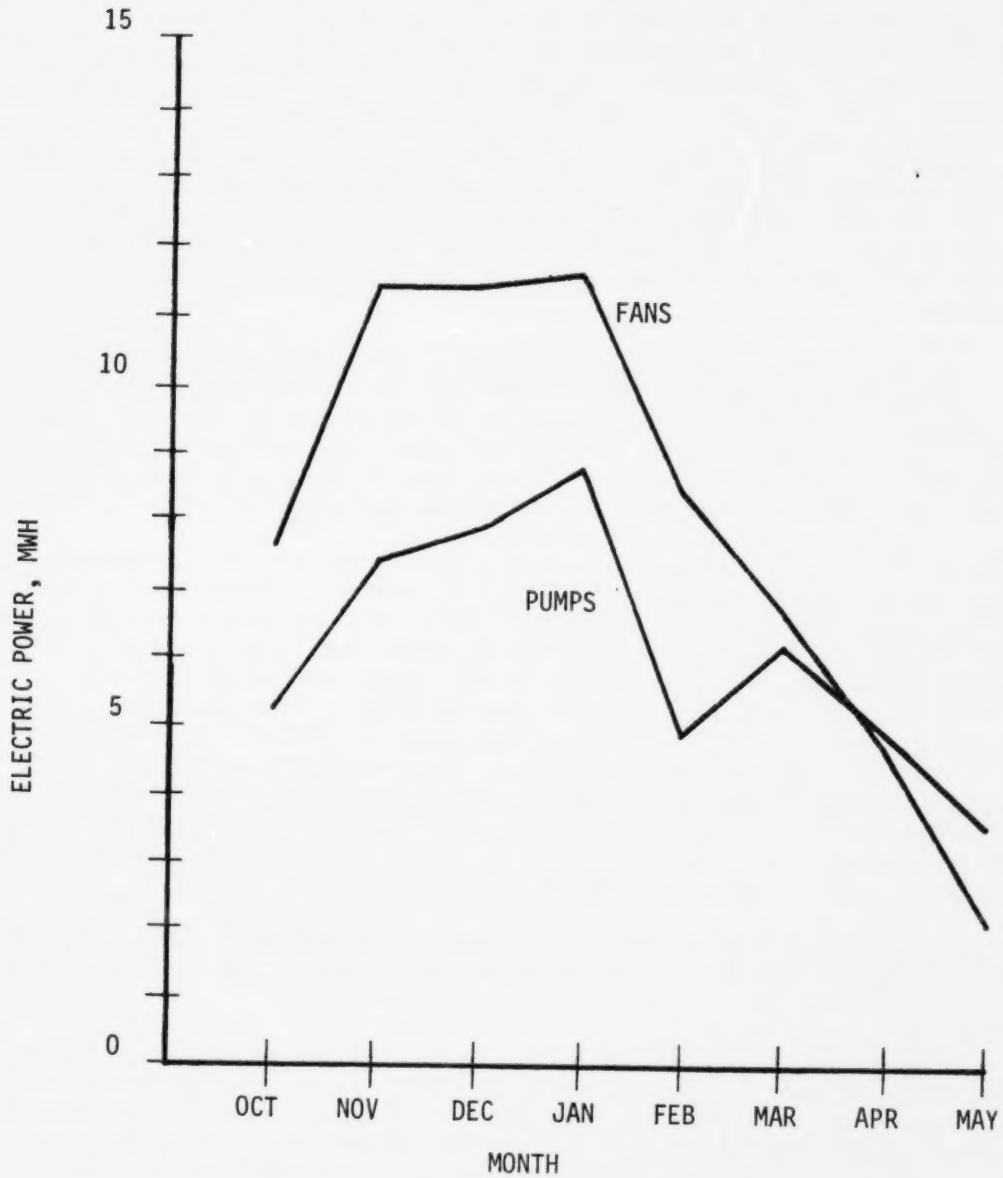


Figure 20 Monthly Electric Power Consumption of Heating Fans and Pumps (1976 - 1977)

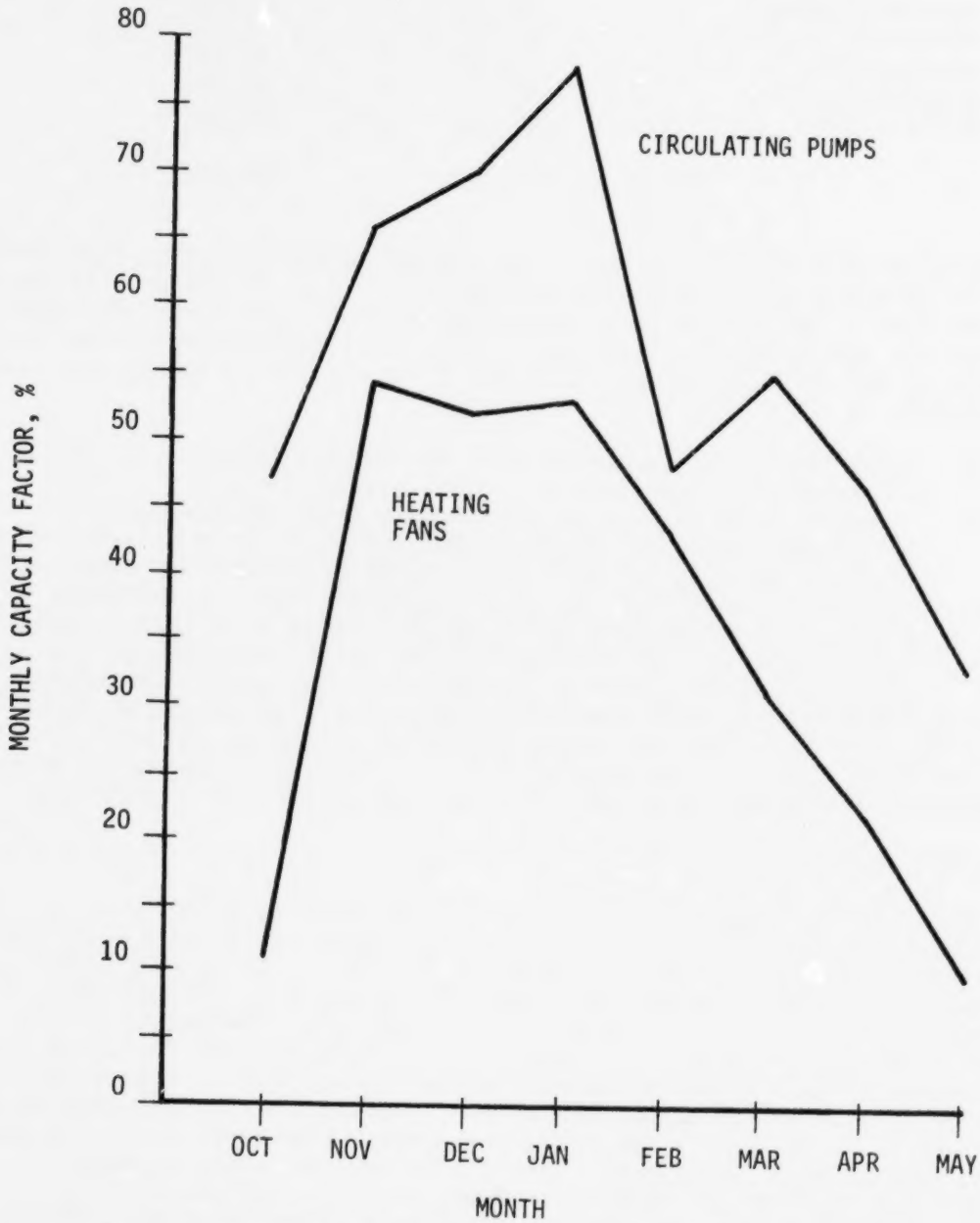


Figure 21 Monthly Capacity Factors of Greenhouse Heating System Units (1976 - 1977)

TABLE 1. SHERCO GREENHOUSE ELECTRICAL POWER CONSUMPTION

Use	10/1/76 - 5/31/77 KWH	6/1/77 - 6/1/78 KWH
Warm Water Pumps	48,647	52,846
Heating Fans	63,766	79,188
Cooling Fans	4,506	10,813
Miscellaneous Use	37,220	56,160
Boilers & Well Water Pump	249,661	555,793
Total	403,800	754,800

the characteristic monthly energy use by the Sherco Greenhouse boilers during times of generator unit outages during the 1976-77 heating season. It should be noted that 32,500 kwh of the supplemental heat was used during May when the pipeline was taken out of service. Thus, the adjusted supplemental heat discounting May was 217,161 kwh, or 13.9% of the calculated annual heat energy requirement.

The second heating season was similar to the first except that almost twice as much backup heat was required. This was due to several factors, the most important being fouled heat exchangers, lower average condenser outlet water temperatures, pipeline failures, and pipeline unavailability in August, September, and October, 1977 necessitated by commercial expansion of the waste heat pipeline system. Based on degree day data, an estimated 151,025 kwh were used for heating during these three months. Hence, the adjusted supplemental heat consumed was 404,768 kwh or about 32% of the annual greenhouse heat requirement. Since this percentage of supplemental heat addition would likely be considered unacceptable by commercial waste heat users, it should be noted that a commercial greenhouse operator, who used the same waste heat source with unfouled (clean) heat exchangers during the same heating season, required only a 10% supplemental heat addition.

WASTE HEAT AVAILABILITY

The pipeline installed to transmit the condenser waste heat 1067 m (3500 ft) each way to the Sherco Greenhouse and back to the Unit I cooling tower basin went into service on September 16, 1976. The main 30.5 cm (12 in) diameter pipeline operated flawlessly until April 25, 1977 when it was taken out of service for cleaning and inspection. However, a 15 cm (6 in) diameter service pipeline that brings warm water into the greenhouse from the main pipeline failed three times during the 1976-77 heating season. These failures resulted in the loss of waste heat service to the greenhouse for 75.0, 21.5, and 29.0 hours during the months of December, February, and March, respectively. Warm water service availability to the greenhouse due to these failures was reduced to 96.6%. However, the overall availability of waste heat at the greenhouse was only 87.9% due to the combined effects of both pipeline failures and generator unit outages. Table 2

summarizes the Unit outages and pipeline failures month-by-month for the 1976-77 heating season.

During 1977-78 heating season warm condenser water was supplied to the Sherco Greenhouse and to commercial greenhouse operators. In order to do this, the pipeline network was expanded and an interconnection to Unit II was made. Thus, waste heat could be made available from either generating unit by manual operation of valves at the point of interconnection of the two units. Normally these valves were operated when operating personnel were notified of a generator unit outage. With this feature it was possible to have a constant supply of waste heat available to the pipeline except for the time it took to switch the valves during unscheduled generator unit outages, and except for a single simultaneous two-unit outage which occurred in May. For a period of 56 hours, Unit I was out of service for annual maintenance and Unit II was intentionally scheduled out for weekend maintenance.

TABLE 2. WARM WATER AVAILABILITY

Month	Sherco Unit I Outages (hrs)	Pipeline Failures (hrs)	Overall Availability of Waste Heat @ Greenhouse (percent)
September 16, 1976	32.0	0	90.5
October	229.5	0	69.2
November	0	0	100.0
December	7.5	75.0	88.9
January	168.0	0	77.4
February	78.5	21.5	85.1
March	0	29.0	96.1
April 25, 1977	0	0	100.0
Total or Average	515.5	125.5	87.9

Table 3 summarizes the weekly overall availability of waste heat at a commercial operator's greenhouse for the period November 2, 1977 to May 31, 1978. Prior to November 2, 1977 the pipeline system was out of service for construction to extend service to commercial operators. While the pipeline continued in service after May 31, 1978, the greenhouse heating season was essentially over. As indicated, for a period of 4848 operating hours an overall availability of 96.4% was achieved.

On a weekly basis during the first heating season, there were only four weeks out of 30 when warm water was unavailable for part of the time. Unavailable service to the commercial greenhouse operations was primarily due to pipeline failures. Two pipeline failures occurred during the heating seasons: one was the failure of a service line from the main pipeline into a commercial floral operation and the other failure involved a main 30.5 cm

TABLE 3. SUMMARY OF WARM WATER AVAILABILITY AND TEMPERATURE

Dates	Service Availability (Hrs)	(%)	85°F or Greater (%)
11/2 - 11/8	156	100	95
11/9 - 11/15	168	100	93
11/16 - 11/22	168	100	92
11/23 - 11/29	168	100	57
11/30 - 12/6	168	100	69
12/7 - 12/13	80	47.6	84
12/14 - 12/20	158	94.0	84
12/21 - 12/27	168	100	74
12/28 - 1/4	168	100	40
1/5 - 1/11	168	100	96
1/12 - 1/18	168	100	98
1/19 - 1/25	168	100	97
1/26 - 2/1	142	84.5	95
2/2 - 2/8	168	100	81
2/9 - 2/15	168	100	98
2/16 - 2/22	168	100	47
2/23 - 3/1	168	100	99
3/2 - 3/8	168	100	87
3/9 - 3/15	168	100	82
3/16 - 3/23	168	100	90
3/24 - 3/29	168	100	92
3/30 - 4/5	168	100	86
4/6 - 4/12	168	100	87
4/13 - 4/19	168	100	92
4/20 - 4/26	168	100	85
4/27 - 5/3	168	100	88
5/4 - 5/10	112	66.7	91
5/11 - 5/17	168	100	92
5/18 - 5/24	168	100	94
5/25 - 5/31	168	100	97
Totals or Averages	4848	96.4	

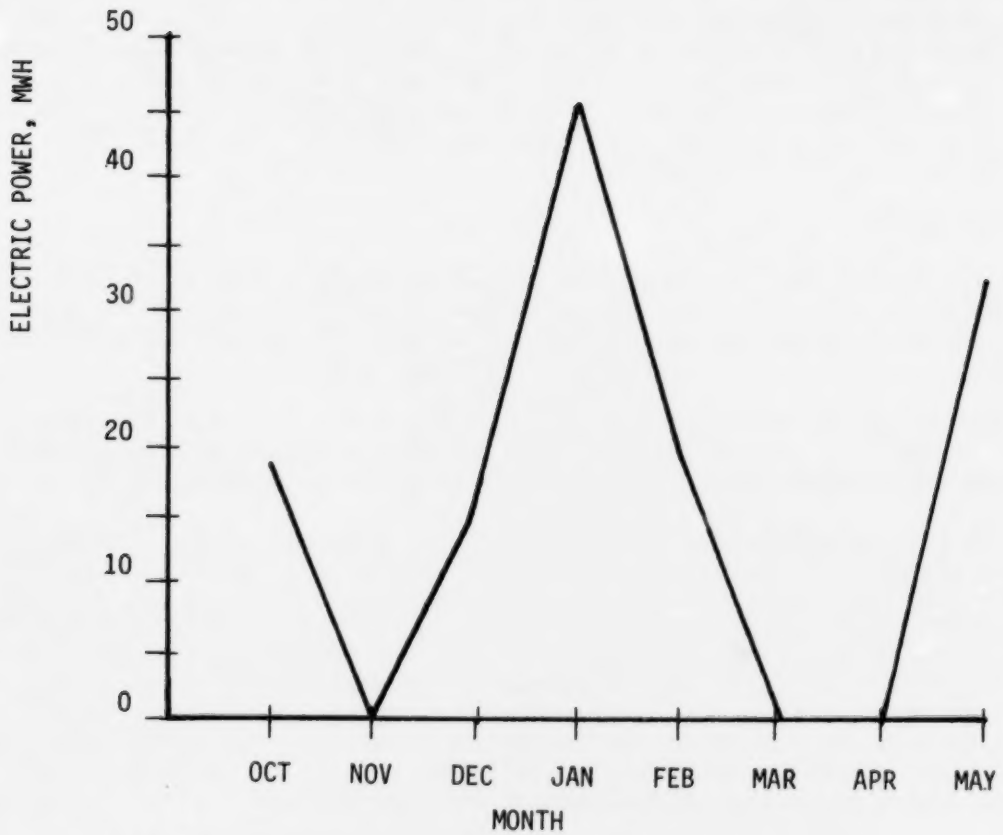


Figure 22 Monthly Electric Power Consumption of Greenhouse Boilers During Unit I Outages (1976 - 1977)

(12 in) diameter plastic pipeline. In the former case, a four-day outage occurred; in the latter case, a 26-hour outage occurred. The period of unavailable service indicated in May was during the previously mentioned two-unit outage of the generating station.

It is also noteworthy that warm water at the power plant condenser outlet was available at a temperature greater than 29.4°C (85°F) for 85.4% of the time. However, the actual temperature delivered to the Sherco Greenhouse was somewhat lower due to pipeline heat losses. Figures 23 and 24 illustrate typical piping heat losses from the condenser outlet to greenhouse inlet for warm water taken from Units I and II, respectively. The temperature drop is greater during daylight hours when pipeline flows are low. During periods of higher flows, the ΔT averages about 1.2°C (2.2°F) when the Unit I source supply is used and 3.1°C (5.6°F) when the Unit II source supply is used. The difference in pipeline heat loss for the two sources results from the differences in pipe diameter, pipe material, and total transmission distance. Based on a nominal pipeline flow rate of about 63.1 l/s (1000 gpm), the pipeline heat loss from the Unit I source was about 300 watts/m (312 Btu/hr-ft). This loss rate is about twice that calculated for the design basis with 29.4°C (85°F) water temperature.

OPERATING EXPERIENCE

Construction work on the Sherco Greenhouse began in August of 1975. The greenhouse and the mechanical equipment were installed to provide a commercially oriented demonstration project, which employed systems and practices currently accepted by the commercial greenhouse industry.

The exception to this, of course, was the installation of the warm water air and soil heating systems. The greenhouse system was constructed by union craft labor under the supervision of project personnel.

The heating system was made operational by November, 1975. During the heating season of 1975-76, the greenhouse heating proved to be satisfactory under a simulation scheme. That is, warm water was provided by two - 390 KW (1.28×10^6 Btu/hr) electric boilers at a temperature simulating the anticipated winter design minimum condenser outlet cooling water temperature of 29.4°C (85°F). The first year of operation involved the technical verification of the heating system performance as designed. Preliminary tests indicated that the heating system design was adequate in all conditions experienced, and any problems associated with the initial operation of the various system components were diagnosed and remedied.

On the basis of the successful first year of operation, the connecting pipeline was installed during the summer of 1976 to utilize condenser reject heat from Unit I, which began commercial operation in the spring of 1976. The greenhouse circulation water pipeline source is at a cooling tower supply riser pipe as shown in Figure 25, with circulation flow through the pipeline being provided by the available head pressure at the tap point as developed by the Sherco main circulation pumps.

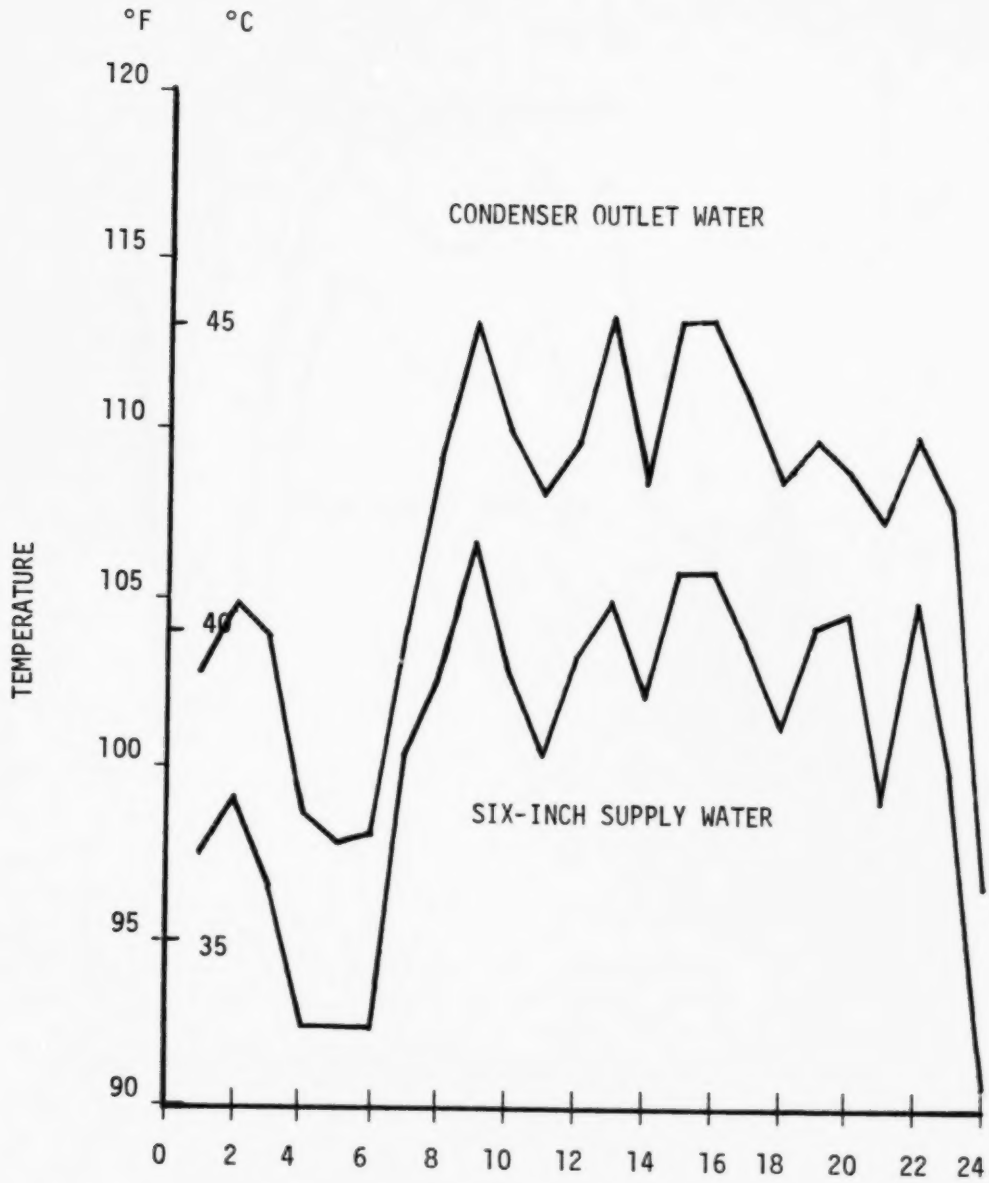


Figure 23 Pipeline Losses Between Unit I Condenser and Greenhouse January 8, 1978

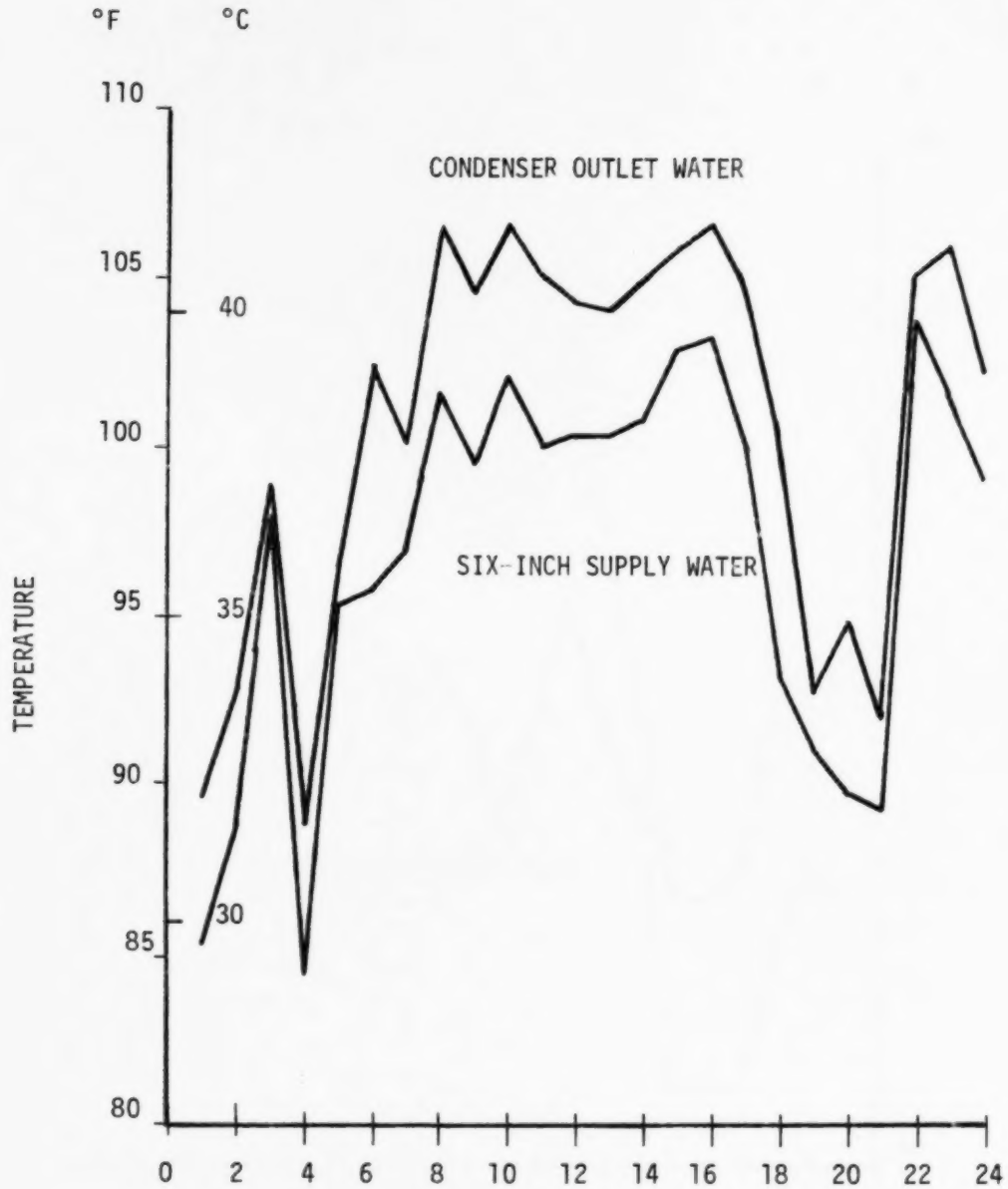


Figure 24 Pipeline Losses Between Unit II Condenser and Greenhouse January 10, 1978

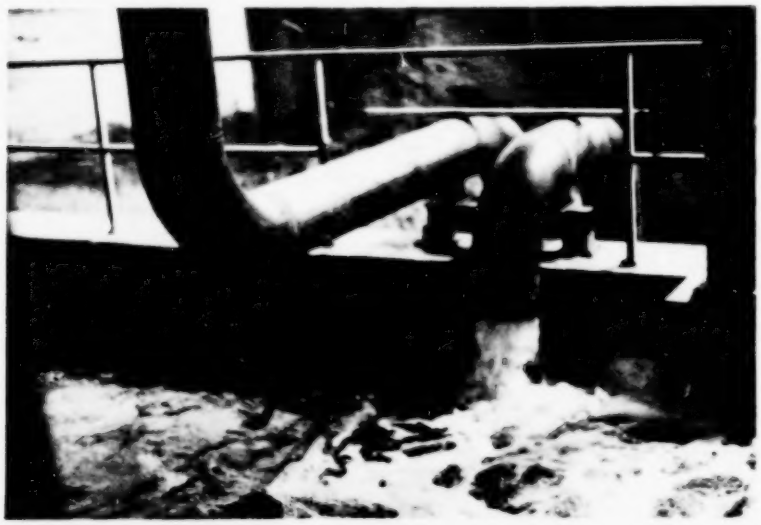


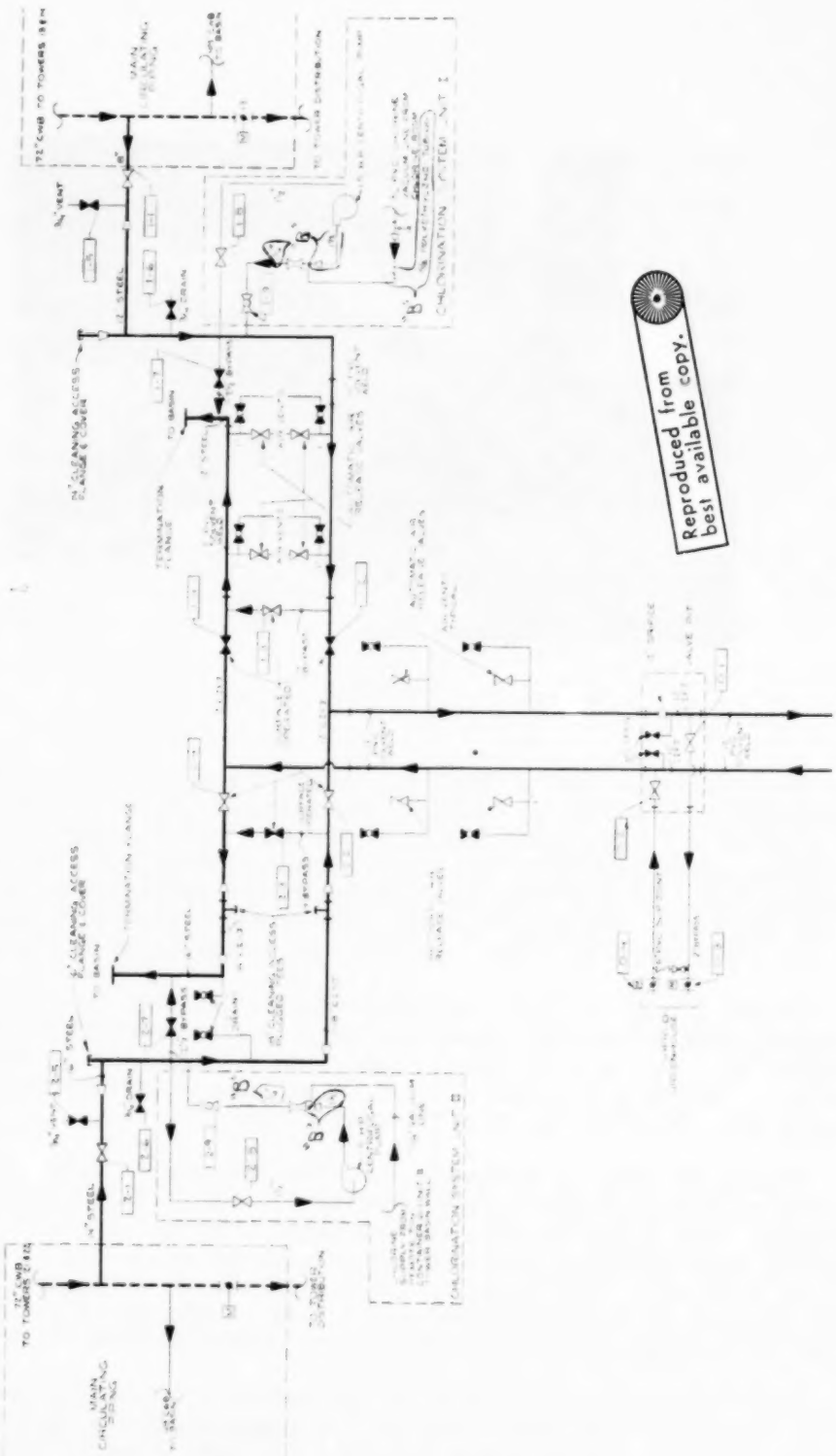
Figure 25 Connection at Cooling Tower

The connecting 1067 m (3500 ft) greenhouse supply and return pipelines consist of 30.5 cm (12 in) diameter low pressure polyvinylchloride pipe. The pipeline is uninsulated and is buried at a nominal depth of 1.52 m (5 ft). The above ground piping at the cooling tower is insulated and heat traced to minimize heat loss and freezing problems during periods when no flow exists in the pipeline. The initial water flow capability of this pipeline was 100 l/s (1600 gal/min) after completion of installation in September, 1976.

In the Summer of 1977, an interconnection between the two generating units was made to provide commercial waste heat service with two-unit reliability. The Unit II supply connection is at a cooling tower riser, similar to the Unit I connection, and a pipeline interconnects to the previously existing pipeline from the Unit I tower.

Figure 26 shows in schematic form the Sherco warm water distribution and service pipeline system as it existed during the 1977-78 heating season. As indicated, the installed Unit II connecting pipeline is a 45.7 cm (18 in) diameter cast iron pipe which is uninsulated and buried to a nominal depth of 1.52 m (5 ft). This portion of the pipeline was intentionally oversized to be capable of delivering sufficient flow to heat up to 5.7 hectares (14 acres) of greenhouses at the present development portion of the Sherco site.

Also indicated in Figure 26 is the method of providing warm water service to the commercial customer. The service connections are installed as a typical utility service, where flow from the main pipeline enters the service supply pipe, passes through a recording flow meter and then is distributed by the user's pumps to the greenhouse heating system prior to being returned to the main return pipeline.



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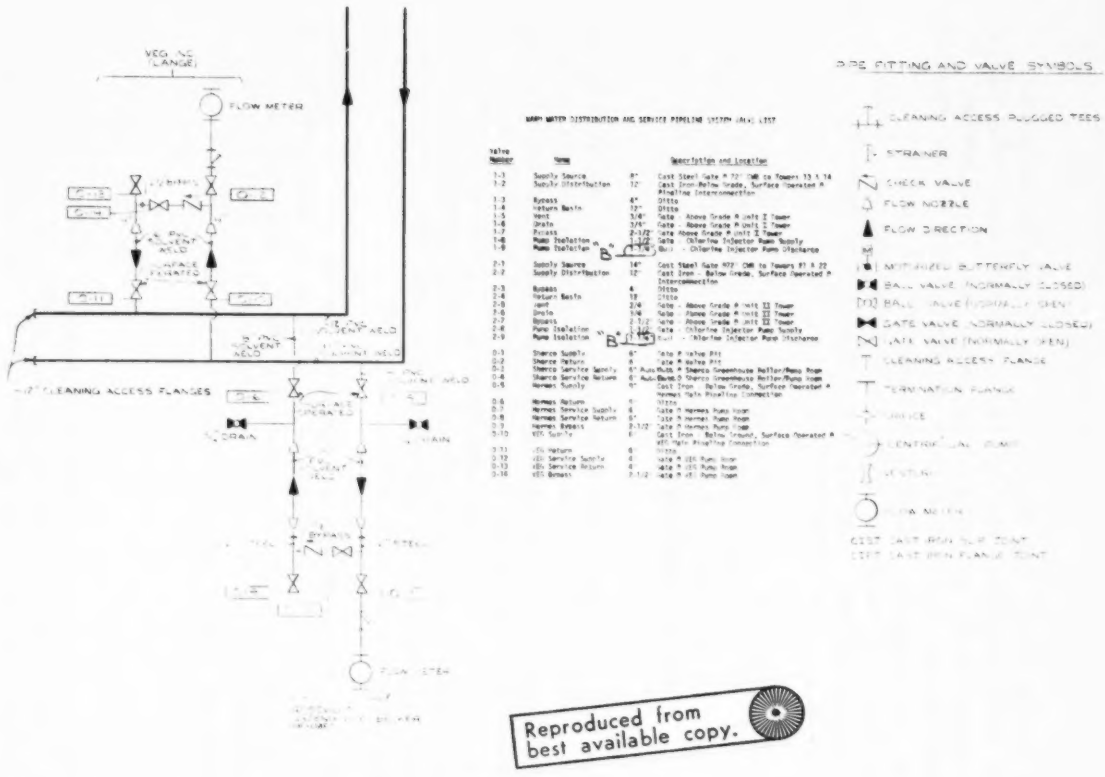

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Figure 26 Warm Water Distribution System Schematic

OPERATING PROBLEMS

Coil Fouling

In November of 1976, after about two months of heating with condenser cooling water, the overall heat transfer capability of the finned-tube coils in the Sherco Greenhouse appeared to be reduced by about 40% from design conditions. Further investigation indicated that waterside coil tube fouling was the reason for loss of performance. Chemical analyses of samples of material deposits from various system components indicated that the fouling was caused by a microbial-based slime. Remedial action in the form of chemical or mechanical cleaning was recommended.

Mechanical cleaning of the coils was investigated, but found to be an unworkable solution. This was due to the difficulty in accessing the tubes in the particular coils used in the Sherco fan/coil units and also to the presence of spiral-wound turbulence-inducing wires on the inside surface on the coil tubes.

Various chemical cleaning programs were also investigated and attempted. Routine chlorination was determined to be the most effective means of slime accumulation control. The removal of the heat exchanger deposits was further complicated by the formation of iron oxide deposits on the interior walls of the carbon steel distribution piping in the greenhouse. It was determined during the 1977-78 heating season that acid cleaning of the greenhouse internal circulation system was the most viable option, and this procedure was adopted as routine maintenance is required.

Based on the experience of the Sherco Greenhouse during 1976-77, general recommendations on system component materials were offered to the commercial customers who installed systems during the summer of 1977. The recommendations were that the finned-tube coils be fully accessible for mechanical cleaning and that distribution piping be of a non-oxidizing, easily cleaned material.

Pipeline Fouling

Concurrently with the fouling of the heat exchangers, a marked decrease in flow capability of the main pipeline was exhibited. The original 100 l/s (1600 gal/min) capability was reduced by about 40% to 60 l/s (1000 gal/min) over the first two months of pipeline operation.

The cause of this flow reduction was indicated again as microbial based slime accumulation on the interior of the pipe walls. It was found that the generating plant's routine chlorination to prevent condenser tube fouling was not effective in preventing fouling of the greenhouse system, because of the location in the circulation system where the condenser water is diverted for the greenhouse system.

The successful solution to the removal of pipeline slime deposits involved mechanical cleaning using polyurethane "pigs" which were propelled

through the pipe by water pressure. After this mechanical cleaning operation, the original full flow capability was restored.

The experience in pipeline and waterside coil fouling impacted the design of the commercial service pipeline as installed in 1977. The pipeline source connections have fittings for mechanical cleaning access. Remote chlorine injection systems were also installed at both the Unit I and II source connections to allow for routine supplemental chlorination to prevent slime formation. Inspection of the commercial grower's heat exchangers and piping system has indicated that the routine chlorination program is effective in preventing slime deposition.

Circulating Water Pump Wear

During the heating season of 1977-78, two instances of seal failure on two of the four Sherco Greenhouse circulation pumps were encountered. Upon inspection of the seals, it was indicated by the equipment vendor that while the pumps had been in service for three heating seasons, the exhibited deterioration was unusual. It was further suggested that the mechanical seal wear was due to the abrasive action of a particulate material suspended in the circulation water. Inspection of the pump impeller and housing indicated no apparent signs of abrasion or wear.

GREENHOUSE SYSTEM OPERATION

The general operation of the greenhouse environmental control system is quite straightforward. With the mechanical equipment automatically controlled, the system as designed requires minimal observation and attention on the part of the greenhouse operator. As is substantiated by the two commercial growers at the Sherco site, the mechanical maintenance routine is equal to or less demanding than that of a conventionally heated greenhouse system.

GENERAL HORTICULTURAL CONSIDERATIONS

SOIL

The greenhouse was constructed on a soil similar to Hubbard loamy coarse sand. This soil exhibits low water holding capacity, low cation exchange capacity and low pH. It was disturbed and reshaped during construction. It was necessary to add pulverized dolomitic limestone, phosphate potash, and nitrogen to a 0-15 cm (0-6 in) depth prior to crop installation. Coarse textured sphagnum moss peat was added to the rose beds at a 1:20 peat-soil ratio to improve the water holding capacity. This had the effect of lowering the pH to 5.0-5.5 and subsequent additions of dolomitic and hydrated lime on the soil surface have not been successful to date in raising the pH to a 6.0-6.5 optimum.

The geraniums were potted in a 3:2:2 and the cinerarias in a 1:1:1 soil-peat-perlite mix containing 5.3 kg/m^3 (5.36 oz/ft^3) of treble superphosphate (0-46-0).

IRRIGATION

The irrigation water was obtained from a ground source. No cooling tower water was used for irrigation. The water quality generally was as follows: pH 7.7, total hardness 213 ppm (as $CaCO_3$), Ca 55 ppm, and Mg 13 ppm. Any potential phytotoxic ions were at insignificant levels.

Irrigation water was applied to the roses using a Gates perimeter system fitted with 180° flat spray nozzles. It was possible to water about 93.6 m^2 (1000 ft^2) simultaneously. A soil tensiometer was employed to assist in estimating soil moisture. Water was turned on at a 10 centibars tension and applied at 12.2 l/m^2 (0.3 gal/ft^2) at each watering. Irrigation frequency was subject to seasonal adjustment.

The cut flower and vegetable crops were irrigated with Viaflow trickle irrigation tubing. The tubing was arranged so that each row of plants was adjacent to a water source.

The potted geraniums were grown on the surface of the heated soil. Sub-irrigation was supplied by capillary mat underlaid with a sheet of polyethylene film. Each mat was 1.22 m (4 ft) wide and wetted by means of three lines of trickle irrigation tubing.

The containerized nursery stock was irrigated with 360° spray nozzles mounted on metal rods and elevated about 0.3 m (1 ft) above the container surface.

FERTILIZATION

Soil fertility levels were determined for soluble salts, pH, nitrate-nitrogen, potassium, phosphorus, calcium, and ammonium-nitrogen on a routine basis at the University of Minnesota Soil Testing Laboratory. Periodic foliar analysis was performed on the roses and on other crops when visual deficiency or toxicity symptoms developed. Fertilizing during crop growth was accomplished by injecting soluble fertilizer into the irrigation lines with a single head injector set at a 1:100 dilution ratio.

The rates of macro and secondary elements were added according to the results of periodic soil tests. Soluble microelement mix was added once to each crop with a low nutrient requirement and twice to crops with high demand. Specific microelements were applied when visual deficiency symptoms were evident. Potted geraniums had a 8 gm (4.6 oz) per pot of Osmocote 14-14-14 mixed into the potting soil after steaming.

Carbon dioxide enrichment was supplied from three propane-fired generators. A timer automatically actuated these units two hours prior to sunrise. The CO_2 level at sunrise was 1500-2000 ppm and was allowed to gradually decrease to ambient during the day.

PEST CONTROL

Steam was not available so, during the July crop changeover, Vapam was used for soil fumigation. The soil was presaturated with water and the Vapam applied at 1 l/10 m^2 (1 qt/100 ft^2) with a hose and suction device. The soil was water saturated again after Vapam application. The area was allowed to dry for 4-5 days, rototilled, and then spot planted with tomato plants. If no phytotoxicity was observed, crop planting into ground beds was resumed. This treatment held weed growth to a minimum and appeared to have reduced damping off in the snapdragon transplants.

Two attempts were made at introducing Encarsia formosa into the tomato crop for biological control of whitefly, Trialeurodes vaporariorum (Westwood). Both attempts proved unsuccessful as the Encarsia population could not expand as rapidly as the whitefly population. Endosulfan 50 WP was used for control after the Encarsia failed.

The two-spotted spider mite, Tetranychus urticae (Koch), infestations occurred mostly on the roses and was controlled with Pentac 50 WP.

Aphids, Macrosiphum spp, on flowering crops were controlled with Aldicarb and on food crops with Malathion 25 WP.

Because of the high air flow from the heating system, botrytis, Botrytis cinerea, did not present much of a problem for most crops. Botrytis infected the leaves and stems of mature tomato plants after cooling pad usage was started.

The rose varieties Sonia and Belinda appeared most susceptible to powdery mildew, Sphaerotheca spp. Applications of Pipron LC and Parnon LC

were used for control.

Rhizoctonia presented the greatest problem in lettuce and geranium. Benlate was used on geranium and nothing was used on lettuce. Few damping off problems were encountered with snapdragons.

HARVESTING AND MARKETING

The Spring 1976 tomato crop was picked at the light pink stage (10-20% ripeness) and bulked into 13.6 kg (30 lb) boxes. These were transported to a Minneapolis retail store where they were graded and packed. Some were retailed at the store and the balance were marketed to other retail stores. Bulk packing and transporting at this stage of ripeness caused excessive bruising and cracking. Better market quality could be obtained if the fruit were allowed to mature on the vine to between 60 and 80% ripeness.

The Spring 1977 tomato crop was graded at the site into U.S. No. 1, 2, and unclassified according to U.S. Standards for Grades of Greenhouse Tomatoes. Grade No. 1 was sized into nested plastic separators with 3 X 5, 4 X 5, 5 X 5, 6 X 5 and 6 X 6 count. Two layers of separators were placed into a 9.1 kg (20 lb) carton. The holding quality of the product under these conditions was much improved. The packed tomatoes were not stored in a cooler but delivered on the same day to another local tomato grower who sold the product through his established market channels.

The Fall-Winter 1976 leaf lettuce was cut, washed and packed into 2.26 kg (5 lb) boxes. Bibb lettuce was packed 24 per box. An excessive amount of labor was required to wash out sand deposited in the plants from the soil. Growing through a plastic film mulch would have done much to prevent this. The finished product was delivered both to a wholesale produce house and also directly to a supermarket.

Blooming geraniums and cinerarias were placed into flats and delivered directly to retail outlets.

The snapdragons were bunched into tens by color and cut to about 1 m (39 in) in length. A plastic sleeve was pulled over the floral spike and the bunches placed in buckets containing preservative. The bunches were transported and sold directly to the wholesale market.

Cut roses were bunched in bulk, placed into buckets containing preservative, and taken to a local grower who performed the grading and marketing. Monthly grading reports showing the quantity and average price for each grading category were kept for the five cultivars.

The selling price for all the produce varied according to the seasonal supply and demand. None of the crops were grown for a contract price. Demand was good most of the time and quality was generally good.

DETAILED CULTURAL METHODS

Table 4 lists the major crops grown and the cropping schedule.

TABLE 4. CROPPING CHRONOLOGY

YEAR	MONTH	CROP
1976	January	Tomatoes started
		Green peppers started
		Roses planted
1976	June	Tomatoes terminated
		Green peppers terminated
1976	July	Snapdragons started
1976	August	Lettuce started
1976	December	Geraniums started
1977	January	Snapdragons terminated
		Tomatoes started
1977	February	Lettuce terminated
1977	May	Geraniums terminated
1977	July	Tomatoes terminated
		Snapdragon transplants started
1977	October	Freesia started
		Tree seedlings started
1977	November	Cinerarias transplants started
1978	January	Geraniums started
1978	February	Cinerarias terminated
		Freesias terminated
1978	May	Geraniums terminated
		Tree seedlings terminated
1978	June	Snapdragons terminated
1978	July	End of project

TOMATOES

Several cultivars of tomato were planted in the two spring crops to determine their yield potential. Table 5 shows the yield of marketable No. 1 and 2 tomatoes.

TABLE 5. YIELD OF MARKETABLE NO. 1 AND 2 TOMATOES

Cultivar	kg (lb) per plant	
SPRING 1976		
Ohio MR-13	2.8	(6.1)
Ohio-Indiana Hybrid O	3.2	(7.0)
Super M	3.2	(7.1)
Tropic	3.4	(7.5)
Eurocross	4.0	(8.8)
Tuckcross 520	4.3	(9.5)

(Continued)

TABLE 5 (continued)

Cultivar	kg (lb) per plant	
SPRING 1977		
Vendor	4.2	(9.2)
Terrific	4.3	(9.6)
Vendor 76	4.5	(9.9)
Bruinsma	5.6	(12.3)
Eurocross BB	5.6	(12.4)
Michiana	5.8	(12.8)
Tropic	6.0	(13.2)
Better Boy	6.5	(14.4)
Tuckcross 520	6.7	(14.8)

Two factors could account for the difference in yield: plant density and soil fertility.

The area per plant for the Spring 1976 crop was 0.24 m^2 (2.60 ft^2), whereas for the Spring 1977 crop it was 0.37 m^2 (4 ft^2). In addition, the general soil fertility of the 1976 crop was too low and the 1977 crop was more optimal.

It should be noted that the differences between the cultivars are only an indication since a totally randomized plot and statistical analysis was not performed.

The Spring 1977 crop was planted primarily to Tropic because the vegetative growth rate of the vine was less vigorous than other red-fruited cultivars and red fruit is preferred. Tropic was planted at the following densities: one bay at 0.32 m^2 (3.4 ft^2) per plant, three bays at 0.37 m^2 (4 ft^2), and one bay at 0.43 m^2 (4.6 ft^2). Table 6 shows the yield per plant for marketable grades No. 1 and 2. As would be expected, a reduction in plant density improved the per plant yield. However, on a per bay basis, it appears that either a lower density with a high yield or a high density with a low yield produced about the same weight yield per bay.

TABLE 6. YIELD VS. DENSITY FOR TROPIC TOMATO - SPRING 1977

Spacing		Yield			
m^2 (ft^2) per plant		kg (lb) per plant		kg (lb) per bay	
0.32	(3.4)	5.2	(11.5)	2176	(4798)
0.37	(4.0)	5.6	(12.4)	2009	(4430)
0.43	(4.6)	6.8	(15.1)	2138	(4714)

SNAPDRAGONS

This crop was grown because there are few local cut snapdragon producers left, and there appeared to be a demand in the local market. This projection proved to be generally true except for the period between Thanksgiving and Christmas when the demand was very low. The crop was generally apportioned into 50% white, 25% yellow, and 25% pink. Seedlings in group 3 flowering classification included about 10% novelty (double flower, butterfly, bicolor) for spring cutting. All snaps were grown as single stem cuts as these generally had better stem and flower spike quality, were more uniformed and flowered earlier. Attempts to program the beds to flower in a sequential order to insure a steady cutting supply proved unworkable. No facilities for photocontrol were available so the bed was cut when it had sufficient floret count and replanted when empty. The only significant problem encountered was a tendency for boron deficiency to occur in the sandy soil. The single layer of Vexar nylon netting tended to shift horizontally when the plants reached mature height. Additional staking and tying of the netting helped solve this problem.

ROSES

Plants were pinched at 1 cm (0.4 in) diameter to provide a heavy yield for Valentine's Day and Mother's Day. At other times selective pruning was practiced to remove unproductive and weak shoots. During June and July the plants were pruned back to 2-3 of the lowest prominent buds produced over the previous year to control plant height. Marketable flowers were generally cut with two, five-leaflet leaves left below the cut.

Night temperature thermostat setting minimums were 15.6°C (60°F) for Cara Mia and Golden Fantasie, and 16.7°C (62°F) for Sonia, Belinda and Coed. The day maximum settings were generally 5.5°C (10°F) higher than the night.

LETTUCE

Discussions with potential buyers for this product indicated a preference for looseleaf cultivars that could be used as salad components and liners. Grand Rapids H5-4 was chosen because of its tip burn resistance and Waldman's for its dark green color appeal. Several beds of Summer Bibb were planted in August to supply a limited market. All varieties fared well through the first crop, but the second yield crop was reduced due to a rhizoctonia infection.

GERANIUMS

Spinter type, F, hybrid geraniums, including Deep Red, Scarlet, Salmon, Snowdon Cheri, Heidi, Rosita and Ringo, were chosen for seed propagation. The night air temperature was maintained at 15.6°C (60°F) for the first 10 weeks after transplanting and then elevated to 18°C (65°F) until sale. Table 7 shows the growing time required from seeding to first petal show.

TABLE 7. GROWING TO FLOWERING TIME - GERANIUMS

Cultivar	Weeks to Flower
Heidi, Snowdon	15
Ringo, Rosita	16
Salmon, Cheri, Scarlet, Deep Red	17

TABLE 8. CROP YIELDS

Crop	Quantity Sold Kg	(lb)	Growing Area m^2	(sq ft^2)	Yield Per Growing Area m^2	(sq ft^2)	Crop Duration
Tomato 1976	11421	(25381)	1062	(11,424)	23.75	(2.22)	6 mo
Tomato 1977	11605	(25791)	929	(9,996)	27.6	(2.58)	6 mo
Leaf Lettuce	1557	(3460)	437	(4,704)	7.8	(0.73)	6 mo
Snapdragons	5489 bunches (w/bunch)		494	(5,312)	11.1	(1.0) Bunches	11 mo
Geraniums	6000 pots		139	(1,500)	4218	(4 pots)	6 mo
Roses	113,082 bunches (25/bunch)		410	(4,410)	275.8	30.17 Bunches	24 mo

CONTAINERIZED TREE SEEDLINGS

A bay of containerized tree seedlings was planted and maintained by Bailey Nurseries, Inc., Newport, MN. The soil was leveled, sprinkled and compacted with a roller to obtain a fairly level, flat surface and covered with a 4-mil sheet of clear polyethylene. The planting consisted of 57,000 Mugho Pine (Pinus mugo), 2,000 Colorado Spruce (Picea pungens), 2,000 Black Hills Spruce (Picea glauca 'Densata') and 2,000 Austrian Pine (Pinus nigra). The containers used were 32 cm (12.6 in) on a side with 100 cells per unit. The cells measured 2.8 cm (1.1 in) diameter and 15 cm (5.9 in) deep. These were filled with a peat-perlite mix, seeded with 3-4 seed per cell and covered with a 0.5 cm (0.2 in) layer of number 2 crushed granite poultry grit. The containers were placed on the polyethylene sheet to prevent root penetration into the soil and also to allow air pruning of any emerging root tips through the bottom drain holes. After emergence the cells were thinned to two plants per cell, then two months later thinned to one plant per cell. When the day length shortened to 12 hours, cool white standard 40-watt fluorescent lights were used to extend the photoperiod to 24 hours. The light intensity measured from 2690 to 3770 lux (250-350 ft-c) at the container surface.

The seeds germinated well and growth was vigorous except for December, January and February. No insect or disease problems were encountered. The containers were removed the latter part of May. By this time the growing medium was well root-bound and could easily be removed by simply pulling at the base of the stem. The average stem lengths in May were as follows: Mugho Pine 15.24 cm (6 in), Colorado and Black Hills Spruce 25.4 cm (10 in), and Austrian Pine 28 cm (11 in).

Two minor crops consisting of freesia (Freesia hybrida) and green bell peppers (Capsicum Annuum) were grown for trial. Neither crops fared very well economically but growing conditions were adequate.

No yield trials were conducted for the soil heating system since it was impractical to implement a totally controlled situation where valid comparisons could be made. It is intuitively felt, however, that the soil heating was beneficial. Verification of soil heating benefits can be obtained by reviewing the literature.

NURSERY STOCK

A propagation trial of deciduous and evergreen ornamental nursery stock was conducted from November 1976 through June of 1977. Hardwood cutting material was rooted directly in the sandy soil using the soil heating system for bottom heat and the trickle irrigation tubing as a moisture source. The tops were hand misted. Hardwood tree seeds were also planted in the soil. Most material germinated and rooted very well.

Removal of the material showed well developed root systems. Shoot growth rates were very rapid as would be expected in greenhouse conditions.

CONCLUSION

The cultural practices followed in the greenhouse were, by and large, standard for this area. From a horticultural standpoint, it was felt that the most advantageous aspects of this heating system were the high air flow which tended to reduce foliar fungal diseases and the soil heating which improved the root environment.

This high air flow did cause foliar burn in the roses during late spring when the plants were tall. This problem could have reduced by 2.9 m (10 ft) gutter height instead of the 2.3 m (8 ft) used.

ECONOMIC FEASIBILITY

A stated goal of the Sherco Greenhouse project was to demonstrate the economic feasibility of utilizing waste heat for greenhouse heating in Northern climates. In order to do so, careful attention was paid to cost throughout the project design, construction, and operation. The data gathered during the Sherco Greenhouse project, along with experience of commercial greenhouse operators who now utilize waste heat at Sherco, support the conclusion that economic feasibility has been demonstrated. In order to maintain the proper perspective, it should be remembered that only the economic feasibility of heating with waste heat has been proven. That is, waste heat has been shown to be competitive on a current cost basis with oil heat. In making the foregoing statement, it is assumed that the waste heat available in condenser cooling waters has no economic value as viewed by the utility. Furthermore, it is assumed that utilities are willing to sell waste heat to users at their operating cost plus a reasonable return on investment to supply waste heat some distance from the power plant. With these assumptions then, what remains to be proven is that it is economically feasible to relocate a vast greenhouse industry to selected power plant sites with suitable and reliable waste heat. This will depend on a number of site and market related variables, but some of the most important considerations have been identified in this project and are addressed here.

HEAT DELIVERY COST AND PRICING CONCEPTS

The cost to deliver heat from the condenser outlet of a power plant to greenhouse customers depends on certain general variables such as distance, total acreage served, pipeline design philosophies, etc. and some site specific variables such as type of soil, climatic conditions, and method of connection to the cooling water system. All of the information presented here is based on the site-specific characteristics of Sherco. While it may be possible to generalize from this experience, generalization should be made carefully with due consideration to the key variables that might differ from site to site.

A 20.3 cm (8 in) tap and valve in a 183 cm (72 in) steel riser pipe at Unit I tower was installed along with a 30.5 cm (12 in) diameter plastic pipeline, extending 1067 m (3500 ft) each way to the Sherco Greenhouse site and back to the cooling tower basin in the summer of 1976. The total cost of this installation, which also included a 15.2 cm (6 in) plastic service line 30.5 m (100 ft) long from the main 30.5 cm (12 in) pipeline into the Sherco Greenhouse and interconnection with the greenhouse heating system, was $84,000. This pipeline was capable of delivering 101 l/s (1600 gpm) from Unit I riser pipe to the Sherco Greenhouse site. The following summer

it was decided to expand the pipeline system to provide waste heat as a utility service to commercial customers. To do so, a 35.6 cm (14 in) tap and valve were installed on a 183 cm (72 in) steel riser at the Unit II cooling tower. This tap fed into a 45.7 cm (18 in) cast iron pipeline that went 305 m (1000 ft) each way to interconnect to the previously built 30.5 cm (12 in) line. Included in this construction also was the cost of extending the 30.5 cm (12 in) pipeline some 213 m (700 ft) one-way distance and two service connections with meters to two commercial greenhouse sites. Also included was the cost of an automatic chlorination injection system to control pipeline bacterial fouling. The total cost of this work was $141,000. The new pipeline was intentionally oversized so that it could accommodate future expansion of up to about 442 l/s (7000 gpm) with some additional future construction. To date then, $225,000 has been invested in pipelines to serve waste heat to present and anticipated customers. Based on this experience and engineering estimates of the cost to further expand waste heat service for the 442 l/s (7000 gpm) initial development, a total investment in pipelines of nearly $600,000, or about $43,000 for each .4 hectare (1 acre) is projected. Using this investment and typical utility financing, the .4 hectare (1 acre) user must pay about $6,000-$8,000 per year for twenty years to completely amortize the investment. This cost is the major cost of serving waste heat to the user, but fortunately, it is a fixed cost once the investment is made. After twenty years, continued operation of the pipeline should be possible, in which case this large fixed cost would no longer need to be charged.

In addition to the capital investment in pipelines, there are operating costs associated with the pumping energy required to deliver the flow to the user and return it, as well as the chemical cost for chlorination, and overall pipeline network operation and maintenance. The calculated energy required to deliver warm water about 1.2 km (4000 ft) at Sherco amounts to .032 kwh/m^3 (.12 kwh/1000 gal). This is based on low pipeline velocities that will eventually increase, increasing the energy requirement in the future. At current NSP internal cost for electricity, the pumping energy costs .048¢/m^3 (.18¢/1000 gal). For a typical .4 hectare (1 acre) plastic greenhouse, the pumping energy would cost $270 per year. Chlorine for bacterial slime control now costs about $550/year which prorates to .044¢/m^3 (.167 ¢/1000 gal). Operating labor and maintenance will be determined with additional experience, but the present allowance for other O&M is .172¢/m^3 (.653¢/1000 gal). Actual maintenance experience in the 1977-78 heating season indicated a cost of .354¢/m^3 (1.34¢/1000 gal) which is considered excessive but typical of a first year of operation. Thus, the total operating cost now stands at .264¢/m^3 (1.0¢/1000 gal) which works out to about $1500 per year for a typical .4 hectare (1 acre) greenhouse.

The total capital and operating cost (experienced and projected) for a 5.7 hectare (14 acre) complex at Sherco then amounts to about $9200 per year for a .4 hectare (1 acre) greenhouse. On the basis of the annual energy required by the greenhouse, this amounts to a cost of $.96 GJ ($1.02/10^6 Btu.

Several points are noteworthy concerning this calculated cost of waste heat. First, this is the current cost, not a twenty-year average cost. In the future cost escalation of pipeline O&M will cause this figure to rise, though a doubling of the O&M cost would only increase the current cost by 16%. Secondly, the calculated cost per unit energy required by the greenhouse is based on a calculated annual greenhouse heat loss of 9548 GJ/year (9050 X 10^6 Btu/yr), which does not include boiler losses for comparable useful heat derived from combustible fuels. And, finally, the instantaneous heat extracted from the waste heat source is based on a ΔT of 8.3°C (15°F), which is only half of the available heat in the waste heat stream since the power plant condenser temperature rise is 16.1°C (29°F). It would be possible, therefore, in some applications to reduce the unit cost of heat by achieving a higher ΔT in the greenhouse heating system. This assumes, of course, that waste heat is sold on the basis of cost of delivery of warm water and not on the basis of value of heat extracted by the user.

The latter possibility suggests that the philosophy adopted by utilities for waste heat pricing can impact the economic feasibility. The impact, whether adverse or beneficial, depends obviously on the philosophies adopted. NSP has decided to attempt to price the first units of waste heat sold on a projected future average cost of serving a defined, in this case 5.7 hectare (14 acre), complex of greenhouses. What this means is that the return on investment deemed acceptable by NSP will not be achieved until the pipeline network installed is fully utilized. The early year losses are initially sustained as part of the development cost of commercializing the concept, but hopefully will be recovered later after the pipeline network is fully amortized. This pricing philosophy is promotional in that it provides service at less than cost for the number of years it takes to fully develop the installed pipeline system. However, the price signal is realistic since it reflects expected future costs so that large increases in price need not occur in the future.

In addition to the general cost of service pricing philosophy, NSP has decided to offer waste heat to commercial users on the basis of long-term, fixed-price contracts. These contracts, currently offered for ten-year periods, are seen as mutually beneficial to NSP and the greenhouse operator. They benefit NSP because of take or pay provisions that guarantee repayment of the large fixed costs associated with the waste heat service, and they immensely benefit the greenhouse operator because energy costs are no longer subject to arbitrary price changes or general inflation. While only the fixed cost of service (i.e., pipeline investment cost) is covered by these contracts, this still stablizes energy cost for the grower because fixed costs are over 80% of the cost of serving waste heat.

The current NSP pricing philosophy has been implemented in the form of a demand and use rate structure for waste heat, or warm water service as it is called. The demand portion of the rate now stands at \$3.42/l/min (\$12.95/gpm) of peak average 15-minute flow recorded by NSP on the customer premises during an entire heating season. The use portion is now .264¢/m^3 (1.0¢/1000 gal) of total flow measured through the recording meter during the heating season. The demand and use rate will be changed each year as cost of service data indicate appropriate; however, for any given customer the demand rate

rate which reflects fixed costs will be held constant for the ten-year duration of the service agreement contract. After ten years the demand rate offered for contract renewal will be that prevailing in the year of renewal. During the period of the service agreement, the variable use charge will be changed yearly according to cost of service data.

HEAT EXCHANGE SYSTEM COST

In order to utilize low temperature condenser waste heat, greater heat transfer surface areas and larger volumes of heated air must be distributed than in conventional greenhouse heating systems. Obviously, this produces an increase in the cost of the heating system, initially, and in the cost of operating the system due to the increased electric energy requirements.

The actual capital costs for all air heating system materials delivered to the Sherco Greenhouse in mid 1975 was $46,662 or $21.98/m^2 ($2.04/ft^2). Table 9 presents a breakdown of the actual cost for Sherco along with an estimate for a .4 hectare (1 acre) commercial greenhouse facility in 1977 dollars. The materials include everything needed for the complete erection of the air heating system and water circulation system including all sheet-metal, dampers, ducts, piping, valves, fittings, flowmeters, wiring, and controls. In the case of the estimate for a commercial facility, a complete back up heating system is included in the cost estimate. The reduction in cost for the commercial system compared to Sherco results from design improvements that were made as a result of the Sherco experience. It should be noted that the costs presented do not include a soil heating system which is not considered a necessary, though perhaps a desirable, part of the basic waste heat heating system.

TABLE 9. WASTE HEAT SYSTEM

Materials Cost Summary (Actual Dollars)

	Sherco Greenhouse Actual[1] Mid 1975	Estimated Commercial Greenhouse[2] Mid 1977
Fan Coil Units and Accessories	21,656	47,000
Circulating Water Pumps, Piping, and Valves	6,764	5,000
Electrical and Controls	18,242	11,000
Back Up Heaters and Fuel Storage	-	11,000
TOTAL	46,662	74,000
$/m^2	21.98	18.59

[1]Sherco Greenhouse Area = 2123 m^2 (22,848 ft^2)
[2]Commercial Greenhouse Area = 3980 m^2 (42,840 ft^2)

The cost to install the waste heat system was not specifically separated from the total labor cost to erect the entire Sherco Greenhouse facility. However, because of the highly prepackaged nature of most of the heating system equipment, it is believed that installation labor would not exceed 25% of the total heating system materials cost. While this percentage may seem low, it should be considered that an entire greenhouse can be erected for about $\$10.76/m^2$ ($\$1/ft^2$). And, 25% of the heating system materials cost amounts to $\$4.52/m^2$ ($\$.42/ft^2$) of greenhouse floor area. In addition, recent commercial experience has shown that an entire waste heat greenhouse facility could be erected for little more than $\$6.56/m^2$ ($\$.61/ft^2$) labor cost, excluding electrical work and some other minor subcontract items. Using an estimated installation cost of 25% of total materials yields a total investment of about $92,500 for a .4 hectare (1 acre) greenhouse complete waste heat system. This figure must then be compared to the cost of the conventional heating system displaced. Estimates vary from about $\$10.26 - 21.52/m^2$ ($\$1.00 - 2.00$ ft^2) of heated floor area for the Minnesota climatic conditions. Using the mid-range of the estimates, a conventional heating system serving a .4 hectare (1 acre) greenhouse would cost about $65,000. The apparent capital cost difference between a conventional system and the waste heat system is about $27,500 for the .4 hectare (1 acre) unit. This differential capital investment must be amortized over the life of the heating system, which is believed to be 20 years, and considered as an added cost of owning and operating the waste heat system.

OPERATING COST COMPARISON TO CONVENTIONAL SYSTEMS

The operating costs for a greenhouse facility using waste heat depend on the price charged for waste heat, the availability and temperature of the waste heat, the cost of electricity to operate the heating system, and the cost of backup or supplemental fuel. During the operation of the Sherco Greenhouse Project, accurate records were kept and the cost of all elements are known. However, because the Sherco Greenhouse heating system was designed before the cost of waste heat was known, it probably uses a higher peak flow rate than can be justified on a commercial basis. The Sherco Greenhouse uses the same total flow for air and soil heating as does a commercial facility which is almost twice as large. However, the commercial greenhouse was designed when the cost of waste heat was known. Therefore, the operating experience and projections based on the commercial facility are presented here.

The comparative operating costs of utilizing waste heat versus conventional heating are indicated in Table 10. The figures presented are based on a .4 hectare (1 acre) double plastic greenhouse located at the Sherburne County Plant site. The total operating costs on an annual basis for the waste heat system in 1978 are estimated to be $17,000 which includes $8,000 for waste heat, $7,000 for electricity, and $2,000 for standby propane.

A typical conventional greenhouse using No. 2 fuel oil has an estimated heating cost of $28,000 per year. There is an apparent savings of $11,000 per year by utilizing the waste heat system in 1978 dollars. But, the big advantage of the waste heat system is more apparent in the future as fuel costs escalate. The waste heat system would realize an escalation in the cost of propane and electricity, but the waste heat costs would not increase

very much due to the fact that the pipeline investment had been made 20 years previously. In 1998, at a compound escalation of 6% for all utilities and variable operating costs, the waste heat system shows a cost advantage of $51,000 per year. These comparative operating costs are projections based in part on operating experience and anticipated operating experience at the Sherco site.

The actual operating costs for all utilities for the .4 hectare (1 acre) commercial floral range totaled $3.98/m^2 ($.37/ft^2) for the period November-May. This compared to $7.00/m^2 ($.65/ft^2) for a glass greenhouse owned by the same company. While part of the savings is attributable to the fact that one greenhouse is double polyethylene and the other is glass, probably only 30% of the savings results from that difference. The remaining savings, about $.86/m^2 ($.08/ft^2), directly result from the use of warm water for heating. This actual experience in the first year of commercial operation of the warm water heating system falls considerably short of the projected annual savings of roughly $11,000 for a .4 hectare (1 acre) unit, but the greenhouse with which the comparison was made received 62% of its energy as interruptible natural gas. Had the other greenhouse been heated only with oil, the comparative savings would be about $13,000.

TABLE 10. COMPARATIVE OPERATING COSTS OF WASTE HEAT VERSUS CONVENTIONAL HEATING

	- 1978 Costs -		- 1998 Costs -	
	Waste Heat	Conventional	Waste Heat	Commercial
Fuel Cost				
Standby Propane	2,000		6,000	
#2 Fuel Oil		31,000		95,000
Electricity	8,000	1,000	26,000	4,000
Waste Heat Cost	8,000		10,000	
Total Per Acre Per Year	18,000	32,000	42,000	99,000

Basis: #2 Fuel Oil @ $.45/gal
Propane Cost @ $.43/gal
Electricity Cost @ $.035/kwh
Escalation @ 6%

In terms of overall commercial acceptance of waste heat, there are other considerations that are very important. One of these is the distance from the market. Most new electric power stations are located some distance from major metropolitan centers for reasons of air quality and other considerations. Therefore, the source of waste heat is not close to the market for greenhouse products. The increased transportation costs must be considered

by the prospective greenhouse operator in determining whether he can relocate to a power plant site to use waste heat. A second consideration is the cost of land and the manner in which land acquisition is handled. At Sherco, NSP owns all of the land adjacent to the power plant. The land on which the commercial greenhouses are located is leased land. Therefore, they will never benefit from the appreciation in land values which in the past has generated significant long-term capital gains for greenhouse owners. Thus, in cases where land will be owned by a utility and leased to greenhouse operators, significant savings in operating costs are necessary to offset the disadvantage of leased land. Another consideration may be the local property tax structure. Generally speaking, the value of a power station impacts local property tax rates to the extent that property taxes tend to be low in areas in which power plants are located. This can have a beneficial effect on the commercial greenhouse operation.

While it appears economically feasible to provide waste heat service to greenhouse customers and it appears reasonable for the greenhouse customers to make additional investments in heating systems to save in future heating costs, it is still too early to predict whether this trend will hold true at many power plant sites in the U.S. or whether this will prove to be a relatively unique situation.

Appendix A

BACKGROUND

Northern States Power Company began its investigation of beneficial use of waste heat from its power plants in 1970. At that time, all of the Company's generating facilities employed once-through cooling. Some of the plants used "helper" cooling towers to meet thermal effluent standards. However, none of the stations were operated on a closed-cycle basis.

A nuclear plant under construction at that time near Red Wing, Minnesota (Prairie Island) was designed for closed-cycle operation. A coal-burning plant in Sherburne County, also closed-cycle, was on the drawing board. The warmer temperatures expected from closed-cycle design encouraged research engineers at the Company in their efforts to investigate waste heat applications.

The Agricultural Experiment Station of the University of Minnesota was invited in December, 1970, to participate in discussions concerning the waste heat problem. Possible agricultural enterprises where warm water might be economically attractive were suggested. The response from University scientists was enthusiastic. From that time on, the Company and the University worked in a close partnership to explore all possibilities.

The University formed two three-man teams comprised of agricultural engineers, horticulturists and soil scientists to study along with others at the University, at NSP and elsewhere, the best ways to use the then unused heat in the cooling water. NSP provided financial support for the study.

It soon was evident that little use could be made of the warm water from the once-through cooling generating plants. Discharge water temperatures in winter when it could be used for heating were approximately 10°C (50°F), or about the permitted 10°C (18°F) above the ambient temperature of the intake water at 0°C (32°F). Most heating applications for enclosed plant production or residences required temperatures of 15.5°C-21.1°C (60°-70°F). Even use for soil heating showed little promise because few crops grow well at temperatures of 10°C (50°F) or lower. Frost protection was considered but soon rejected because water droplets cool to ambient air temperature if they travel 4.6-6.1 meters (15-20 ft) through the air. The main consideration in frost protection is the release of heat, 334,934 KJ/kg (144 Btu/lb), by the water as it changes state from liquid to solid, i.e. to ice.

The review of heating requirements for various applications and the projection that all, or nearly all, future steam electric generating plants would operate on a "closed-cycle" basis eventually led to the warm water greenhouse project. NSP's closed-cycle designs called for condenser dis-

charge temperatures of no less than 29.4°C (85°F). If water temperature reductions during delivery from condensers to the use point could be limited to 0.5-1.7°C (1-3°F), then an operating differential between the source water and the use environment of 5.5°C-11.1°C (10°-20°F) could be expected. It appeared that adequate heat transfer could take place for heating structures, if equipment were properly sized and operated.

Some of the research projects and demonstration work studied by the teams of University agricultural scientists included:

(1) The Environmental Research Laboratory, University of Arizona and its "total energy" pilot study at Puerto Penasco, Mexico

(2) Oak Ridge National Laboratories greenhouse work led by Dr. Sam Beall and William Furlong

(3) Commercial vegetable greenhouses in Cleveland, Ohio and Houston, Texas

(4) Wright Roses, Cranbury, New Jersey

(5) Eugene Water and Electric Board, Eugene, Oregon

(6) Federal Water Quality Laboratory, Corvallis, Oregon

(7) Dr. L. L. Boersma, Oregon State University

(8) TVA, Muscle Shoals, Alabama

Most of these visits and preliminary studies took place in 1972 and 1973.

It was at this time that a joint decision was made by NSP and the University of Minnesota to seek financial support from the U.S. Environmental Protection Agency for a greenhouse demonstration.

The objectives of the project were:

(1) Utilize energy that is being wasted as a basis for an overall program to conserve natural resources.

(2) Demonstrate methods, using readily available equipment, of economically and reliably heating and managing a greenhouse with waste warm water from the condenser of a power plant.

(3) Encourage private operators to build their own greenhouse at the power plant site to take advantage of a low-cost form of energy.

(4) Determine the costs and problems associated with building, operating, and maintaining a warm water supply and return pipeline at a multi-unit plant.

Early in the development of the greenhouse waste heat project, consideration was given to the use of power plant warm water for cooling purposes as well as heating. It was reasoned that if cooling a structure with warm water proved to be practical, greenhouses could be used as supplementary horizontal cooling towers. This concept was investigated in a pilot project which will be described later in this report.

One of Northern States Power Company's stated goals: "To contribute to the quality of life where we serve by: (1) demonstrating active stewardship of the environment and of the use of natural resources, and (2) sharing our varied corporate resources with those who need help" was accomplished by this project.

The NSP Sherburne County Generating Plant (Sherco), located 45 miles northwest of the Twin Cities, was the site selected for the project. Sherco is a two-unit coal-fired plant with a total rated output of 1360 MW. It has closed-cycle mechanical draft wet cooling towers for thermal pollution control and a limestone scrubber system for air pollution control. The first unit began commercial operation in May, 1976, with the second unit going on line in May, 1977. The condenser cooling water flow rate for each unit is 15.77 m^3/s (250,000 gpm) with a design cooling water temperature differential, ΔT, of 16.1°C (29°F). The winter design minimum temperature of the water at the condenser outlet is 29.4°C (85°F). This is the design temperature of the warm water for the greenhouse heating system.

The Company owns more than 1200 hectares (3000 acres) of land adjacent to the power plant. Space has been allocated for: (1) a greenhouse development, (2) a 137 hectare (340 acre) University Sand Plain Agricultural Experiment Station Farm and (3) an industrial park.

The soil in the area is a loamy, coarse sand, and the topography is nearly level. Excellent drainage conditions permit greenhouse construction without drain tiles. The soil conditions and topography make the installation of warm water supply and return pipelines connecting the greenhouse to the power plant relatively easy.

In 1973, with the energy crisis beginning to surface, the emphasis on waste heat projects began to shift from thermal pollution control to energy utilization and conservation. It was becoming increasingly difficult to justify, economically, construction of greenhouses at power plant sites in sufficient numbers to significantly reduce thermal pollution. For example, it would require 405 hectares (1000 acres) of greenhouses to use the heat rejected by a 1000 MW plant under conditions of operation at the Sherco plant.

Appendix B

PILOT PROJECT

While the application for EPA funding was pending, NSP, with the University's commitment of technical assistance, developed a small pilot project to "prove the concept" of heating greenhouses with waste heat in a northern climate.

Previous research work conducted in the U.S. had concentrated on using evaporative cooling pads with saturated air to provide both latent and sensible heat transfer for greenhouse heating. In this research work, it had been found that high humidity occurred in the greenhouse itself; therefore, the potential existed for increased disease problems in similarly heated greenhouses. In addition, the difference in climate in Minnesota compared to Southern states where the other greenhouse research work was being conducted suggested that a heating system design suitable in one area might not be suitable in another.

Because of the considerable concern regarding whether an evaporative approach would work, it was decided to design a dry finned-tube heat exchange system of sufficient size to transfer the required heat from 29.4°C (85°F) water to heat a 204 m^2 (2,200 ft^2) greenhouse which was owned and operated by a commercial florist in Minneapolis. In addition to the finned-tube system, an evaporative system was installed in series to allow total flexibility of operation for either heating or cooling with the evaporative system, heating only with the dry finned-tube, or heating with both the evaporative system and the finned-tube system. In addition, the pilot research greenhouse heating system was designed to operate in a constant heat rejection mode. Outside air could be introduced automatically so that the heat exchange equipment had a constant inlet air volume and temperature and a constant inlet water volume and temperature. Thus, a constant heat load would appear on the heating system regardless of the actual heat demand of the greenhouse.

The pilot research greenhouse was designed in the fall of 1973 and put into operation in the spring of 1974. The greenhouse was operated in the heating mode in March, April and May of 1974, and evaporative cooling tests with warm water were run in the summer of 1974. Additional heating system tests were run in the winter of 1974-75. As a result of the operating experience in the pilot research greenhouse, it was concluded that using very warm water, up to temperatures of 46.1°C (115°F) on an evaporative cooling pad, resulted in no measurable sensible cooling of the ventilation air for the greenhouse. While large heat rejection rates could easily be achieved, there was no particular benefit to the greenhouse, since the resulting greenhouse temperature (but not humidity) could have been achieved just as

easily by mechanical ventilation only. As a matter of fact, a more satisfactory environment could be achieved by using recirculating well water (at lower temperature than warm condenser water) on an evaporative cooling system rather than trying to reject waste heat.

The heating experiments, on the other hand, revealed that the 29.4°C (85°F) warm water source temperature was adequate to maintain greenhouse temperatures above 12.8°C (55°F) throughout the 1974-75 winter heating season. It was tentatively concluded at that time that the required area of finned-tube heat exchanger was not excessive for installation directly in the greenhouse, but that the fan power requirement was relatively high. It was also concluded that temperature drops of more than 10°C (18°F) would be very difficult to achieve with finned-tube exchangers without adversely affecting the internal air temperature of the greenhouse. It was further concluded, based on rather limited tests of direct evaporative heating of the greenhouse, that the resultant fogging and high humidity conditions would not be acceptable to commercial floral operators. It should be remembered that the research work reported was conducted in an existing commercially-owned and operated greenhouse, so there was not complete freedom to conduct tests that would result in conditions in the greenhouse considered adverse to the production of a commercial crop. Nevertheless, the overall conclusion of the pilot research project was that waste heat properly utilized with finned-tube heat exchanger systems could create an environment that was comparable with that obtained with other heat sources currently used in the greenhouse industry. It was believed that such a system could be designed, installed, and operated at a cost that might be competitive with the cost of alternative fuels in the future.

It was also concluded that the notion of a constant heat rejection rate permitting greenhouse functioning as a horizontal cooling tower for the power plant was impractical since it required continuous operation of a fan and air handling system considered to be an excessive energy consumer in the first place. This consideration [in conjunction with the considerations that it would take more than 405 hectares (1000 acres) of greenhouses to reject all of the heat from a 1000 MW power station and that evaporative cooling with waste heat from a power plant provided no particular benefit for the greenhouse] suggested that the idea of greenhouses replacing cooling towers, perhaps, could and should be set aside until such time as the basic concept of utilizing waste heat for greenhouse heating could be demonstrated to be commercially viable and of commercial interest. From this experience, then, the foundation was laid for the development of the more commercialized system designs utilized in the Sherco Greenhouse project.

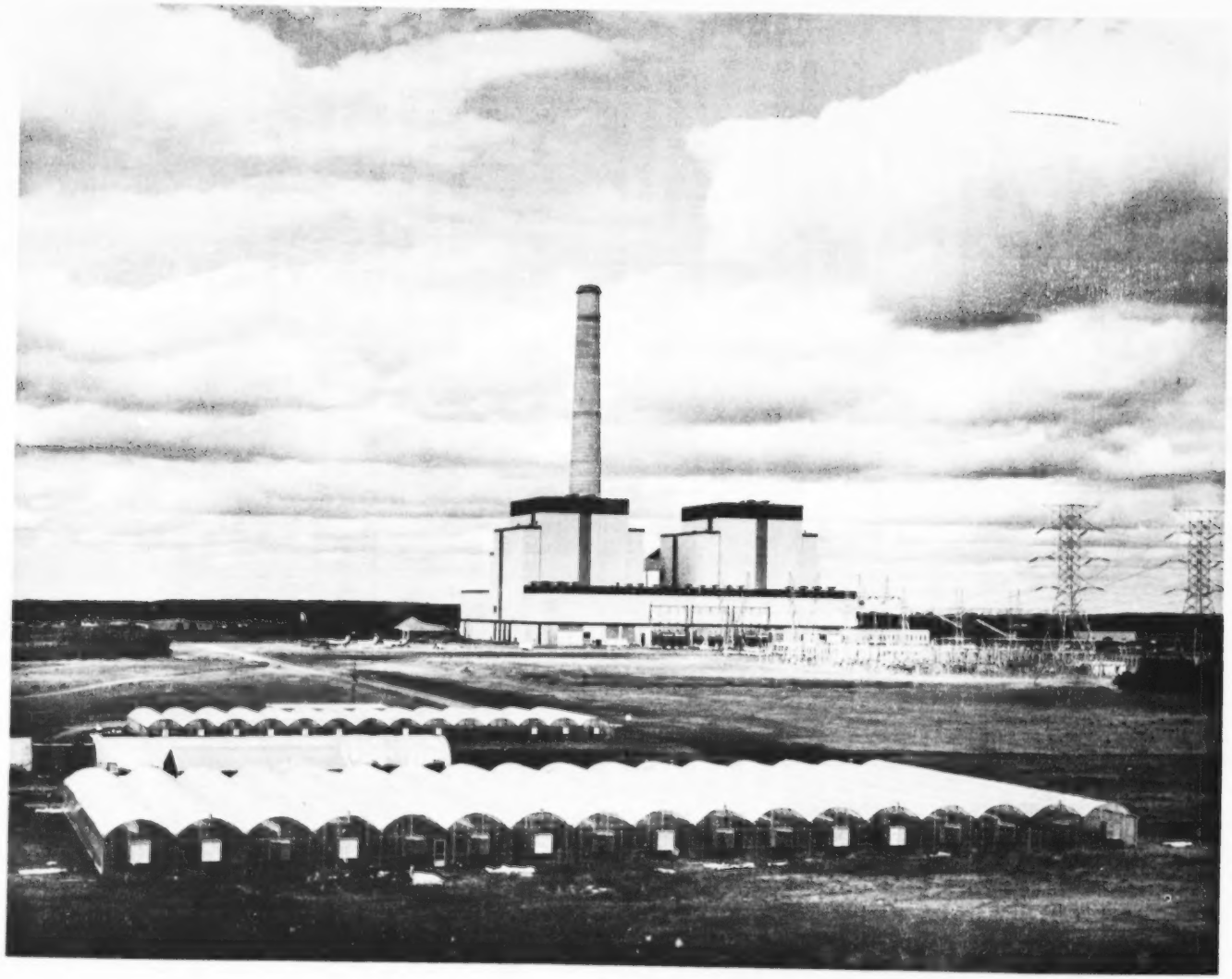

Figure 27 Sherco Power Plant and Greenhouse Complex